Appendix A

SWAT Model Calibration and Use for Bacteria Loading Estimates in the Upper Santa Cruz River Subwatershed

October 2018

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1 SWAT Overview

The Soil and Water Assessment Tool (SWAT) is a public domain model used to simulate the quality and quantity of surface water and predict the environmental impact of land use and land management practices. The SWAT model was chosen for an initial scoping simulation of bacteria loads because the hydrologic model had already been developed, serving as an efficient starting point for simulations. It should be noted, however, that the ability of the SWAT model code to simulate bacteria is limited.

The SWAT model has contained routines for evaluating bacteria fate and transport since SWAT 2000, with subsequent improvements, and has been used in a number of bacterial assessment studies (Benham et al., 2006). SWAT focuses on manure as a source of bacteria (along with point sources and septic tanks); thus manure inputs (including wildlife) must be specified to simulate bacteria. There is no direct provision for urban nonpoint sources of bacteria, although these can be represented to some extent as a "manure" application to urban pervious areas. No bacterial load is associated with washoff from impervious surfaces.

SWAT simulation of bacteria on the land surface includes sorption to the soil, die-off/regrowth, percolation into the deep soil, and transport to the stream in both dissolved and sorbed phases. Once in the stream, bacteria are subjected to an exponential die-off process that varies with temperature; however, the relevant decay parameter is specified at the basin level and cannot be varied by stream segment. The SWAT2009 theory manual states that SWAT also simulates bacterial interactions with sediment. Specifically, when sediment settles bacteria can be removed from the water column, and when sediment is resuspended this can add to the bacterial load, although the concentration of bacteria associated with resuspended sediment is stated to be calculated with an empirical four-parameter regression equation that is not subject to user input control. However, despite these statements in the manual, it does not appear that these bacterial interactions with stream sediment are actually implemented in the SWAT2009 FORTRAN code.

Benham et al. (2006) and Gassman et al. (2007) discuss several additional limitations in the SWAT representation of bacteria. Among these are (1) soil die-off is a function of temperature, but does not take into account the role of other factors, such as soil moisture; (2) bacterial leaching is simulated, but these bacteria are assumed to die-off in the subsurface and there is no representation of subsurface bacterial transport, which is particularly important in areas where subsurface agricultural drains are installed, and (3) the instream representation of bacteria is simplistic and does not account for sorption to solids, storage in the sediments, or factors other than temperature that modify the die-off rate. In addition, all bacterial simulation models must deal with the fact that observed data typically show high levels of random variability, and analytical methods also often have relatively low precision.

Despite these limitations, SWAT provides a useful platform for investigating the bacterial mass balance in a watershed. Model simulations for bacteria should be regarded as one line of evidence in a weight-of-evidence approach – especially as the inherent levels of uncertainty in simulation models for nonpoint bacteria loading are expected to be high. One of the most appropriate uses of such a model is to evaluate hypotheses regarding the spatial distribution of bacterial loads and the potential significance of different source types, conditional on model input assumptions.

2 Hydrologic Simulation

The SWAT model application for bacteria is built upon an existing SWAT model calibration for hydrology that was developed by researchers at the University of Arizona in conjunction with the Santa Cruz Watershed Ecosystem Portfolio Model (SCWEPM), a joint initiative of the U.S. Environmental Protection Agency's Ecosystems Research Program and the U.S. Geological Survey U.S. – Mexico Border Environmental Health Initiative and Geography Analysis and Monitoring Programs. The model was originally developed in SWAT2005 and subsequently converted to SWAT2009. The development and calibration of the SWAT hydrologic model is documented in Niraula et al. (2012). Mr. Niraula, a graduate student at the University of Arizona, kindly provided the hydrologic model and modified executable code to support the bacteria simulations conducted as part of this Clean Water Plan (CWP).

2.1 Hydrologic Model Development

The SWAT model is constructed by discretizing the land surface into Hydrologic Response Units (HRUs) that represent an overlay of land use/land cover, soils, and slope characteristics. Standard procedures and spatial datasets are readily available for SWAT model development in the U.S.; however, extending SWAT models into Mexico is more challenging due to differences and mismatches in data availability, especially for land use and soils. The National Elevation Dataset provides a digital elevation model that covers the entire Santa Cruz River watershed; however, land use/land cover and soils present greater challenges. USGS supported important work to develop a unified land use/land cover dataset for the entire watershed at a 30 m resolution (Villarreal et al., 2012). Finally, Niraula et al. (2012) combined state-level soils data (STATSGO) for the U.S. with more limited information from the United Nations Food and Agriculture Organization (FAO) for the Mexican portion of the watershed.

The geographical extent of the SWAT model is presented in Figure A-1. Note that the extent of the hydrologic model is greater than the Upper Santa Cruz River (USCR) project area identified in the CWP. The hydrologic model was calibrated for the entire Santa Cruz River. The water quality model was calibrated for the USCR from the headwaters to Tubac, including the portion of the drainage area in Mexico. The USCR project area, identified in the CWP, is the area between the International Border and Tubac, including the U. S. portion of Nogales Wash and Potrero Creek (see red outline in Figure A-1).

Niraula et al. (2012) specifically used the 1999 land use map (15 categories) and classified slopes into three classes (0-5%, 5-10%, and > 10%). The overlay process used minimum thresholds of 1% for land use, 5% for soil, and 10% for slope class to reduce the total number of HRUs created. Fragments falling under these thresholds were adjusted back into the more dominant classes. The final model has a total of 131 subwatersheds (from the headwaters to downstream of Cortaro) and a total of 2,583 HRUs.

Individual HRUs range in size from 0.002 km_2 to 18.8 km_2 and there are 2 to 53 HRUs per subbasin. The model includes representation of point sources from three wastewater treatment plants within the U.S. (Nogales, Ina Road, and Roger Road). The Los Alisos Wastewater Treatment Plant in Nogales, Sonora, Mexico was completed in 2012, after the calibration time period and was therefore not represented in this model. Model calibration used weather data from multiple stations in the U.S. and Mexico covering the period 1960-2007. The weather data was subsequently updated through the end of 2010 and the updated files were included with the modeling package provided by the University of Arizona. The period for which the weather data are developed means that the model cannot be compared to water quality data obtained after 2010.

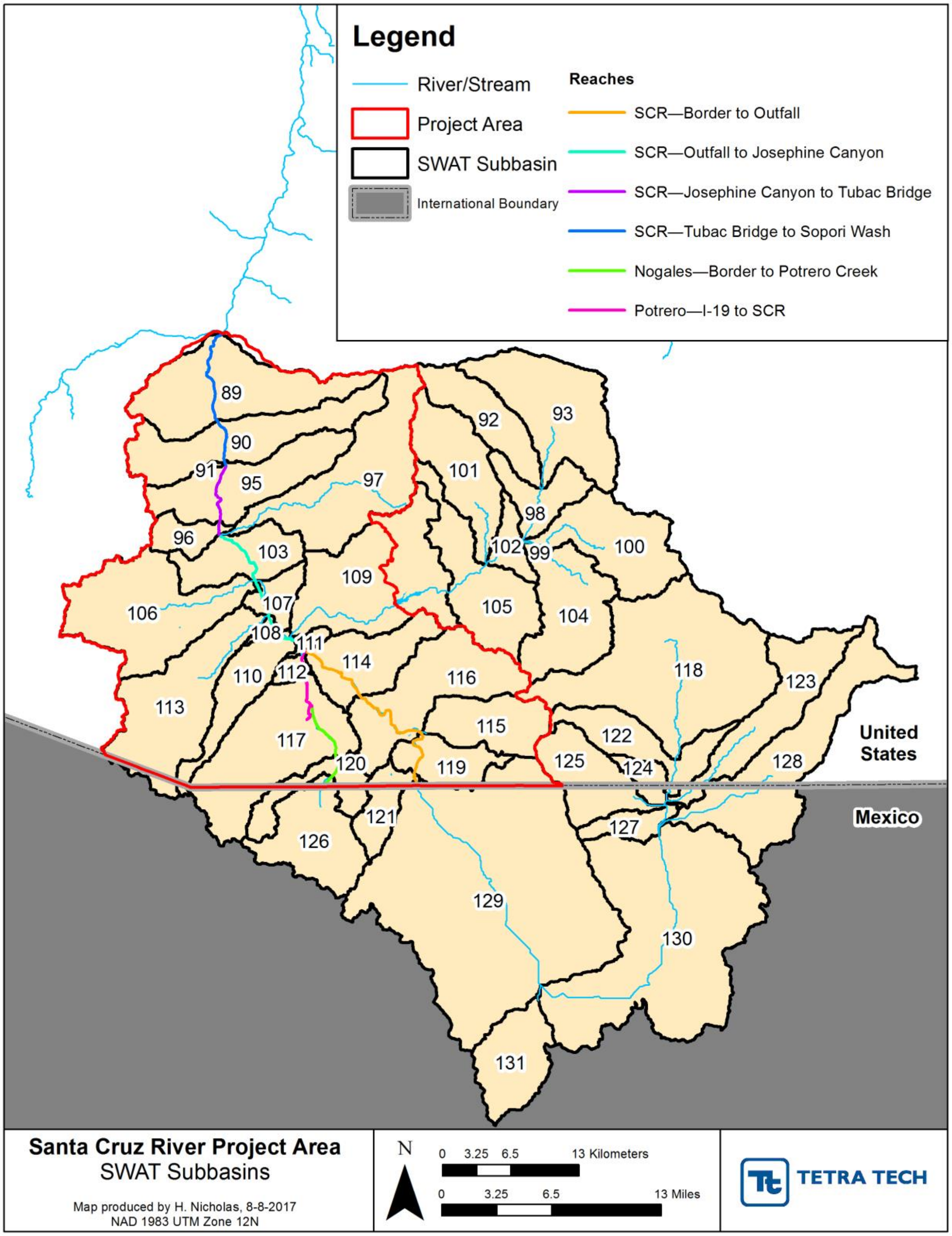

Figure A-1. SWAT Model Subbasins Calibrated for Bacteria in the USCR.

2.2 Hydrologic Model Calibration – Monthly Time Scale

Niraula et al. (2012) calibrated hydrology in the SWAT model to records from seven USGS gage stations on the mainstem from Nogales to Cortaro. Performance of the calibration was evaluated both visually and through three statistical measures: the coefficient of determination (R_2), the Nash-Sutcliffe coefficient of model fit efficiency (NSE), and the percent bias (PBIAS), as recommended for SWAT by Moriasi et al. (2007). All evaluations were made on monthly flow volumes. A reasonable model fit was obtained considering the difficulties typically encountered in simulating flashy desert systems, with monthly NSE values ranging from 0.61 to 0.90 during calibration (0.41 to 0.85 for validation), and PBIAS ranging from -18% to +72% during calibration (-51 to +26% for validation). The fit appears somewhat stronger in the upper reaches from Nogales to Tubac that are of most interest to this study, with a range of PBIAS from -18% to +26% during both calibration and validation.

2.3 Hydrologic Model Calibration – Daily Time Scale

As is typical practice for SWAT, the hydrologic model calibration was evaluated at the monthly time scale. Monthly evaluations, however, do not necessarily guarantee a firm basis for pollutant simulation. Most importantly, a reasonable fit to monthly volume does not guarantee that the correct partitioning between surface runoff and subsurface interflow and groundwater discharge is represented. This flow partitioning can be problematic in SWAT because of the use of a daily Curve Number approach to simulation. It is only the surface runoff that transports eroded sediment and associated pollutants; further, SWAT simulates bacteria load only in association with surface flow (although a delay in delivery is allowed). In addition, runoff loading events typically occur at the scale of hours and days, not months. It is therefore important to examine the ability of the model to represent observed daily flows as well as monthly flows.

There are three USGS gages in the project area (Santa Cruz River at Tubac [gage 9481740] located at the end of the SCR – Josephine Canyon to Tubac Bridge reach, Santa Cruz River near Nogales [gage 9480500] on the SCR – Border to Outfall reach, and Nogales Wash at Nogales [gage 9481000] located on the Nogales – Border to Potrero Creek reach; see Figure A-2); however, the Nogales Wash gage was inactive for most of the SWAT modeling period. Accordingly, the analyses of model fit was performed for daily flows at the Santa Cruz Nogales and Tubac gages (within the area of interest for the bacteria simulation).

The monthly statistics for calibration and validation reported by Niraula were reproduced in the model, confirming a reasonable fit to the monthly water balance for the Santa Cruz River Nogales and Tubac gages. However, the fit to daily flow is much poorer, as shown in the following figures and tables for the whole application period at these gages (see Figure A-3 to Figure A-16 and Table A-1 to Table A-4 for figures and tables summarizing the hydrology model results based on daily, monthly, and seasonal results and observed flow measurements). At the Nogales gage, the monthly NSE is 0.753, but the daily NSE is only 0.065 (Table A-2); at the Tubac gage the monthly NSE is 0.835, while the daily NSE is -0.295 (Table A-4). An NSE near zero implies that the model does not explain the variance in the data any better than does the average value. It may thus be concluded that the SWAT model reproduces monthly and seasonal hydrology adequately for the project area, but has extremely limited ability to predict daily flows and individual storm events. Because loading of sediment and bacteria is driven by runoff events, this situation means that the model will have limited ability to reproduce observed instream concentration data due to imprecision in the hydrology simulation, regardless of other variance components.

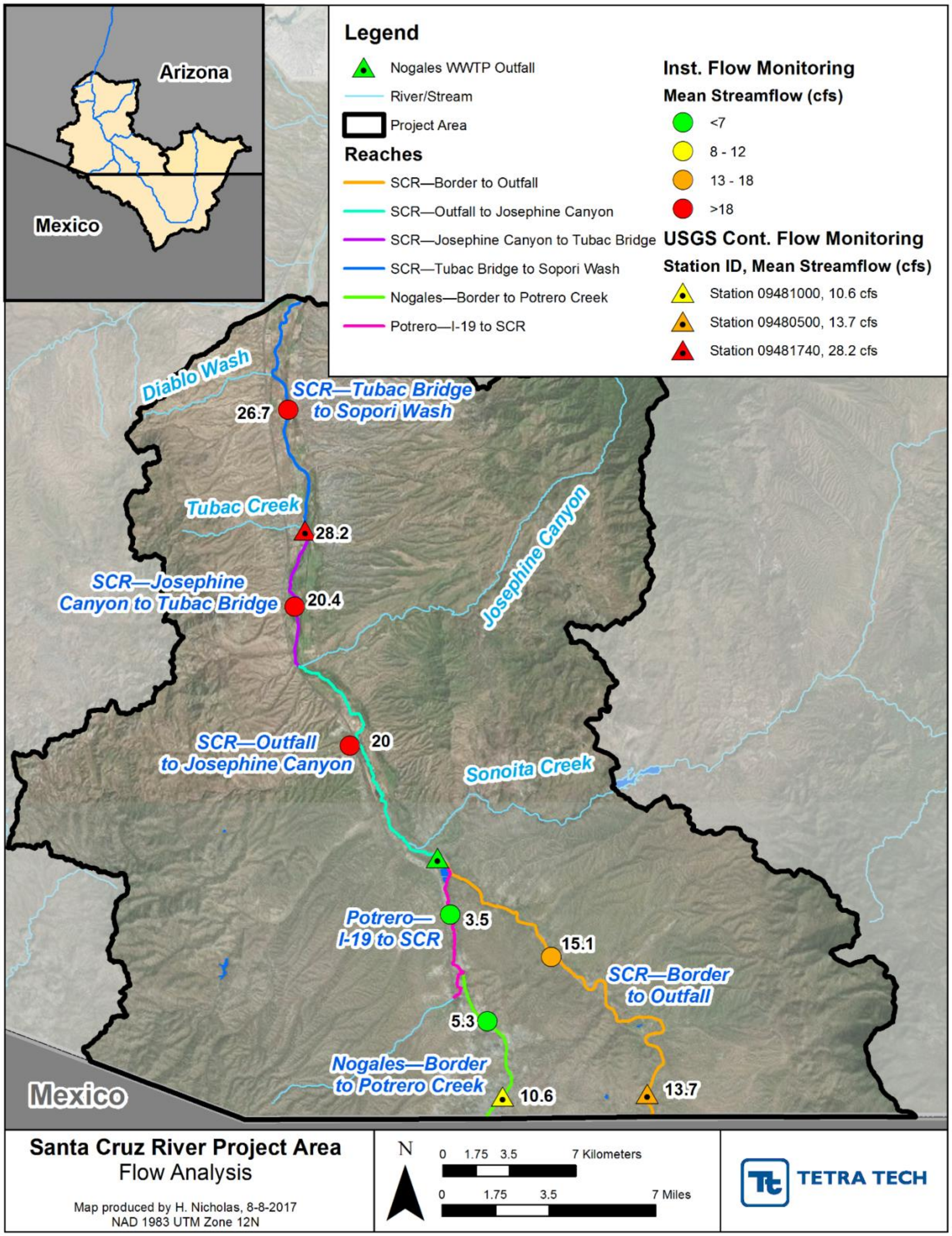

Figure A-2. Flow Gages in the USCR Watershed.

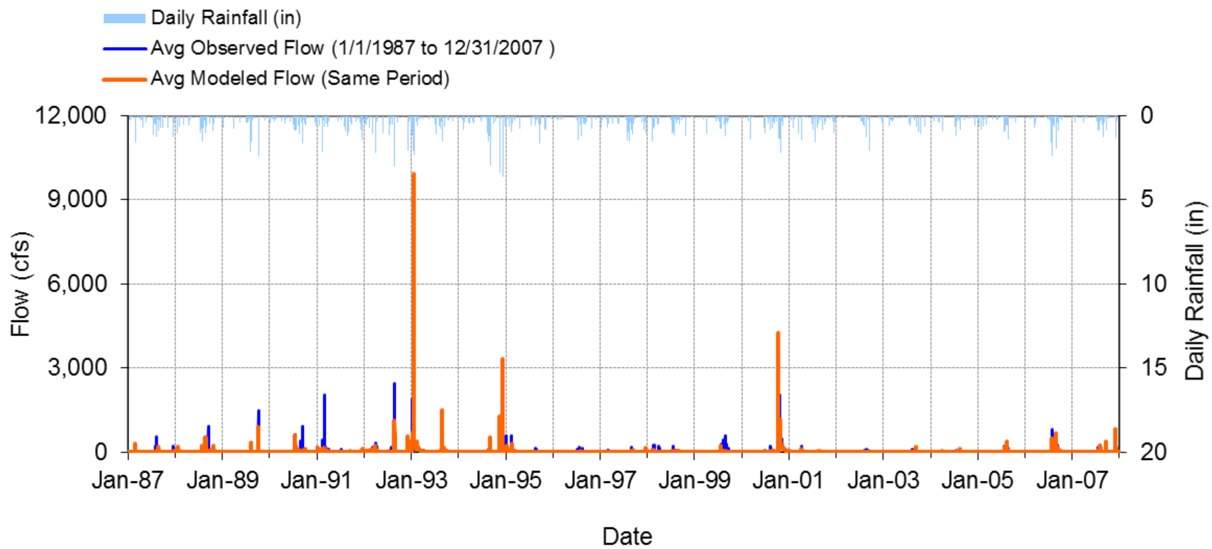

Figure A-3. Mean daily flow: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

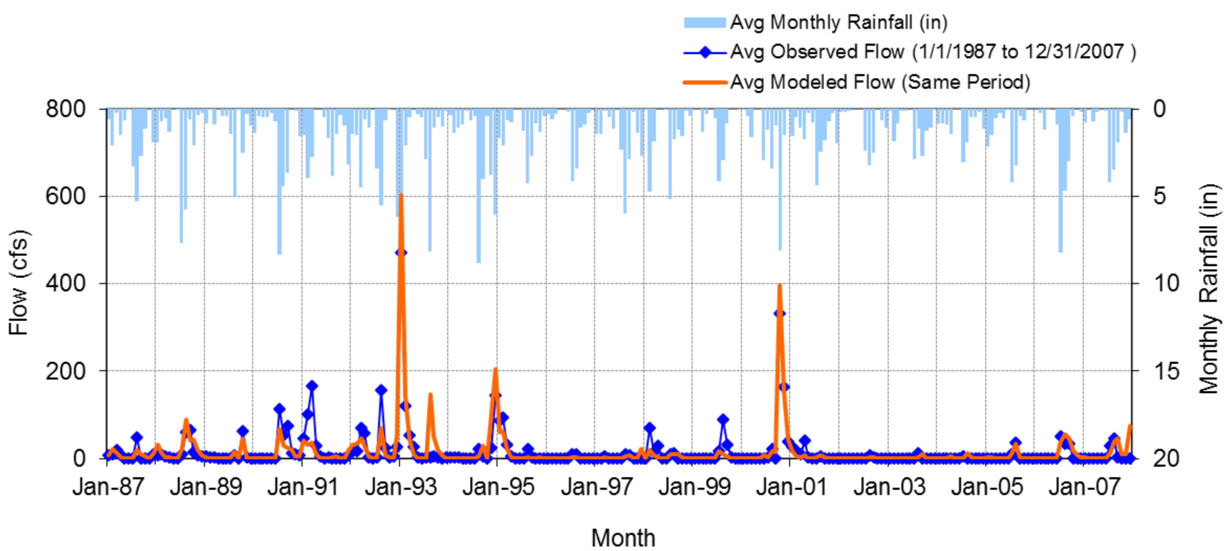

Figure A-4. Mean monthly flow: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

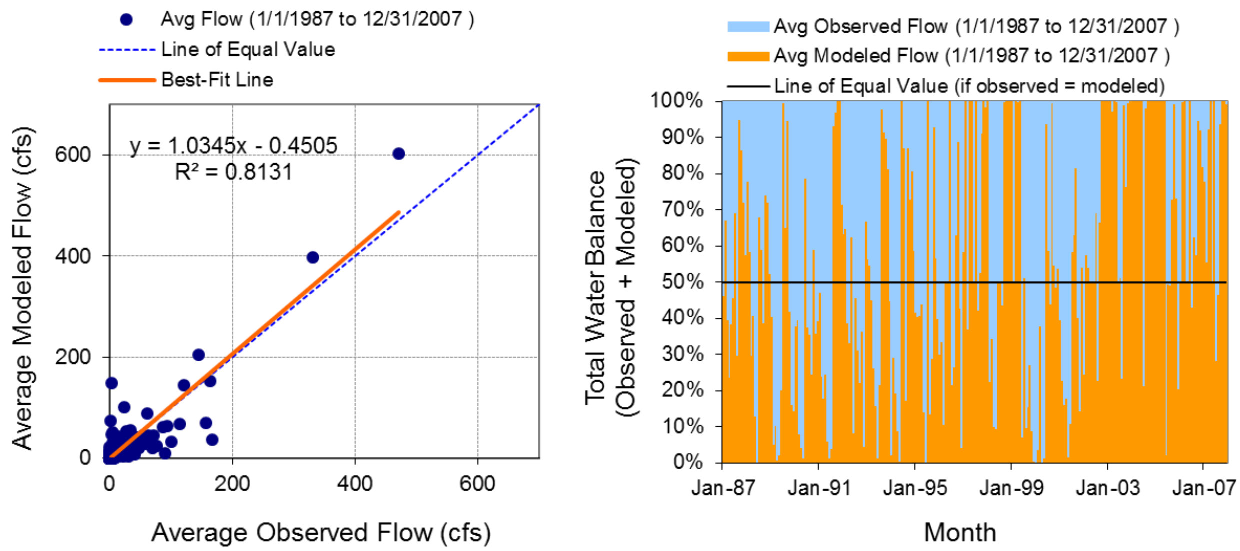

Figure A-5. Monthly flow regression and temporal variation: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

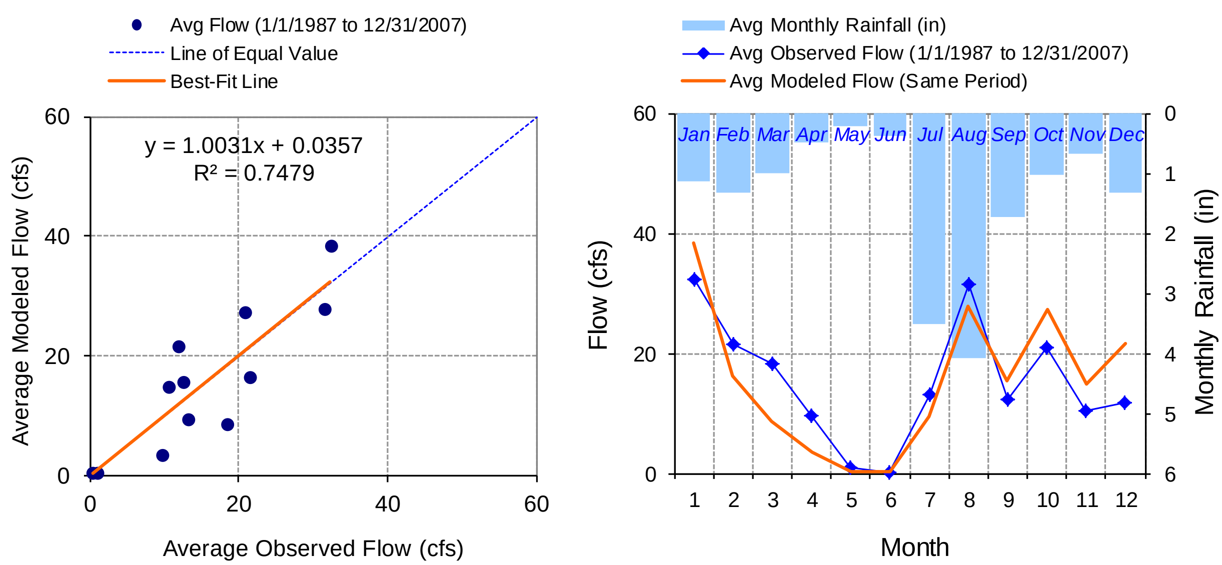

Figure A-6. Seasonal regression and temporal aggregate: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

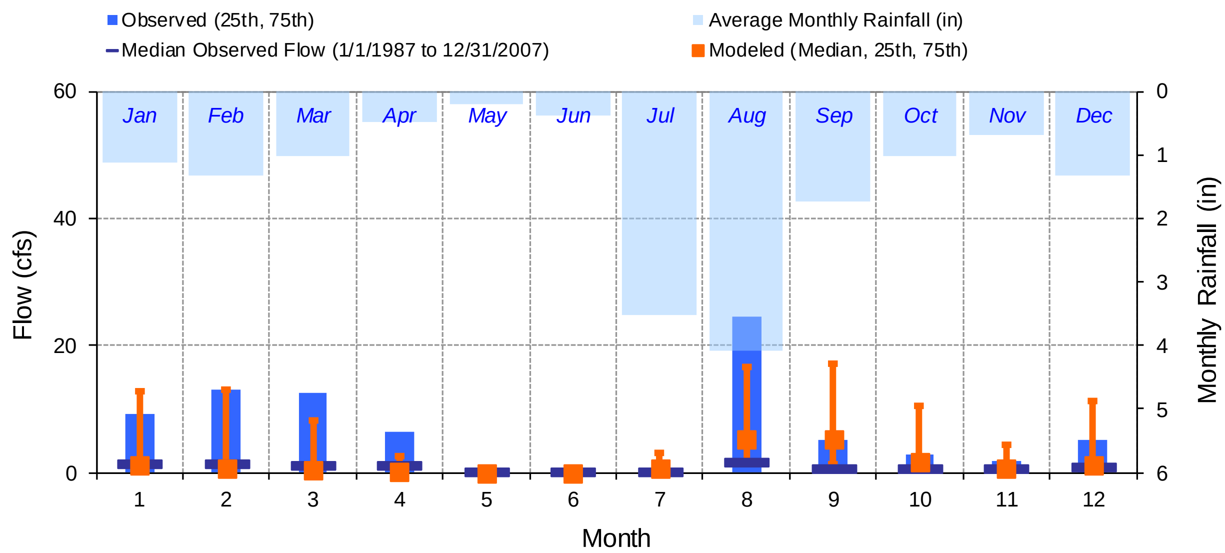

Figure A-7. Seasonal medians and ranges: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

Table A-1. Seasonal summary: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	32.30	1.10	0.00	9.10	38.42	1.07	0.12	12.74
Feb	21.48	1.10	0.00	13.00	16.33	0.72	0.15	13.07
Mar	18.38	0.92	0.00	12.50	8.59	0.49	0.03	8.12
Apr	9.67	0.81	0.00	6.48	3.52	0.09	0.00	2.63
May	0.85	0.00	0.00	0.71	0.34	0.00	0.00	0.04
Jun	0.25	0.00	0.00	0.01	0.39	0.00	0.00	0.00
Jul	13.04	0.00	0.00	0.55	9.39	0.61	0.05	3.02
Aug	31.46	1.30	0.00	24.50	27.83	5.35	1.62	16.57
Sep	12.42	0.30	0.00	5.15	15.49	5.33	1.22	17.08
Oct	20.86	0.27	0.00	2.90	27.25	1.63	0.49	10.53
Nov	10.47	0.48	0.00	1.70	14.92	0.51	0.14	4.35
Dec	11.85	0.66	0.00	5.00	21.53	1.08	0.16	11.18

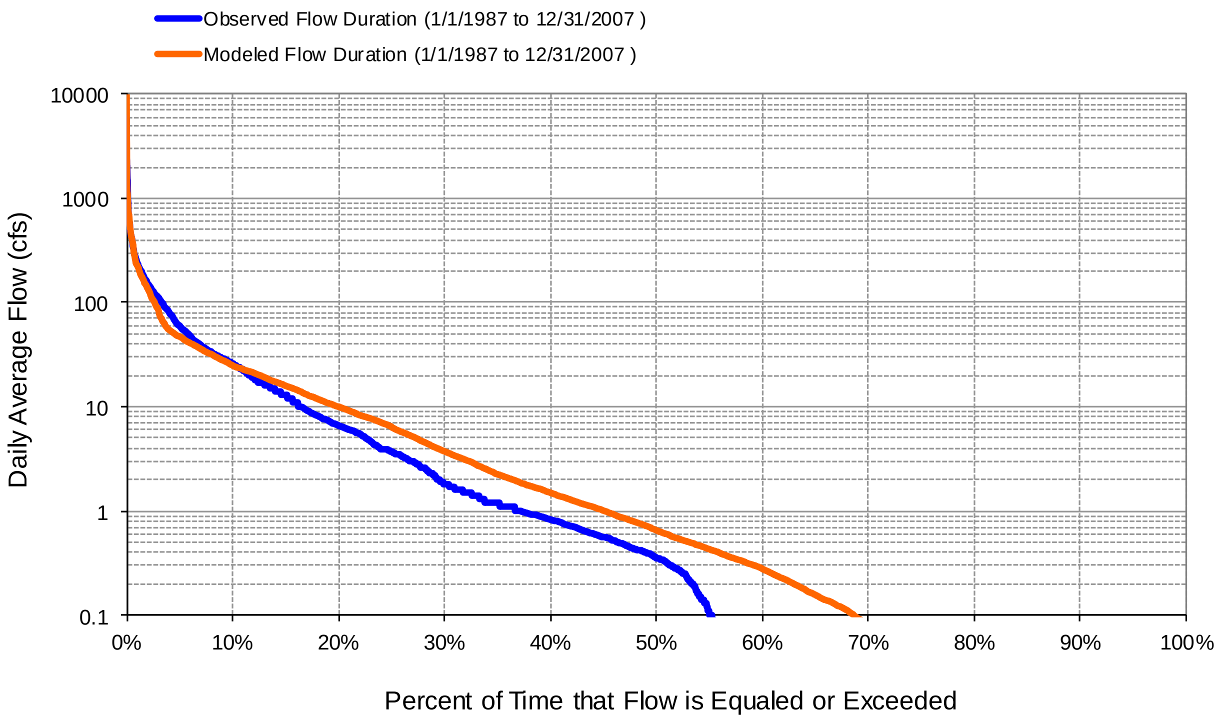

Figure A-8. Flow exceedance: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

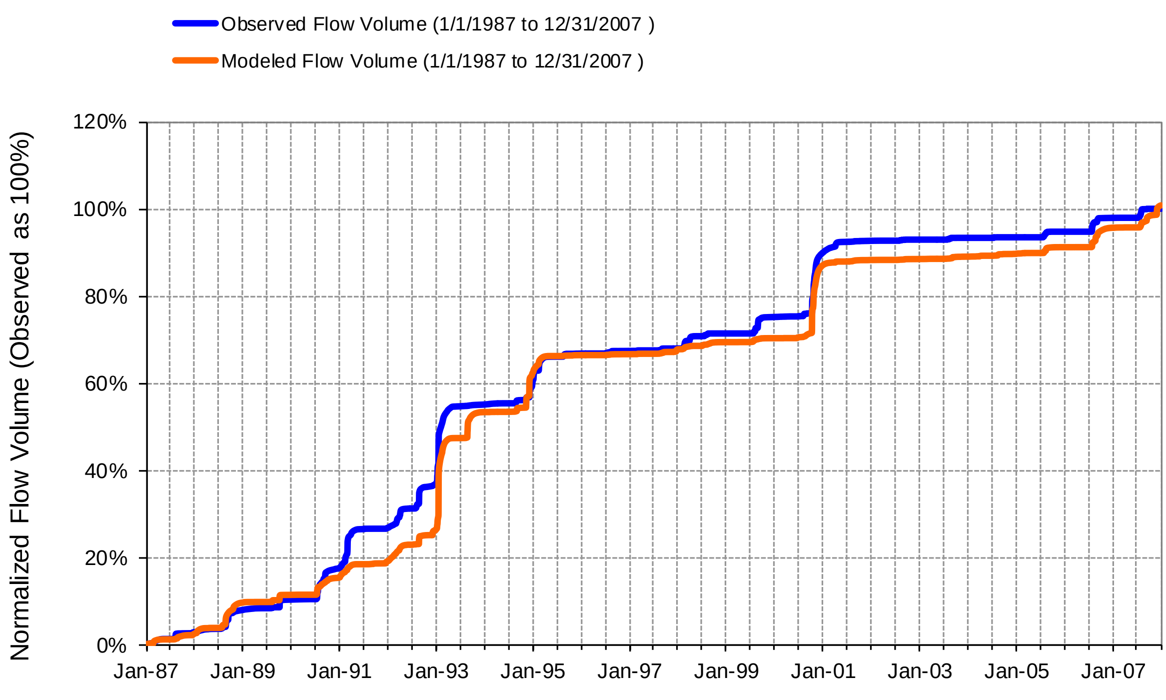

Figure A-9. Flow accumulation: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

Table A-2. Summary statistics: Model Outlet 121 vs. USGS 09480500 Santa Cruz River near Nogales, AZ.

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 121 21-Year Analysis Period: 1/1/1987 - 12/31/2007 Flow volumes are (inches/year) for upstream drainage area		USGS 04980500 Santa Cruz River near Nogales, AZ Hydrologic Unit Code: 04100011 Latitude: 31°20'40" Longitude: -110°51'03" Drainage Area (sq-mi): 533	
Total Simulated In-stream Flow:	**0.39**	Total Observed In-stream Flow:	**0.39**
Total of simulated highest 10% flows:	**0.32**	Total of Observed highest 10% flows:	**0.34**
Total of Simulated lowest 50% flows:	**0.00**	Total of Observed Lowest 50% flows:	**0.00**
Simulated Summer Flow Volume (months 7-9):	**0.11**	Observed Summer Flow Volume (7-9):	**0.12**
Simulated Fall Flow Volume (months 10-12):	**0.14**	Observed Fall Flow Volume (10-12):	**0.09**
Simulated Winter Flow Volume (months 1-3):	**0.13**	Observed Winter Flow Volume (1-3):	**0.15**
Simulated Spring Flow Volume (months 4-6):	**0.01**	Observed Spring Flow Volume (4-6):	**0.02**
Total Simulated Storm Volume:	**0.23**	Total Observed Storm Volume:	**0.25**
Simulated Summer Storm Volume (7-9):	**0.07**	Observed Summer Storm Volume (7-9):	**0.10**

Errors (Simulated-Observed)	*Error Statistics*		*Recommended Criteria*		
Error in total volume:	0.78		10		
Error in 50% lowest flows:	**378.12**		**10**		
Error in 10% highest flows:	-4.73		15		
Seasonal volume error - Summer:	-7.61		30		
Seasonal volume error - Fall:	**47.57**	>>	**30**	Clear	
Seasonal volume error - Winter:	-11.90		30		
Seasonal volume error - Spring:	**-60.49**		**30**		
Error in storm volumes:	-7.63		20		
Error in summer storm volumes:	-25.77		50		
Nash-Sutcliffe Coefficient of Efficiency, E:	0.065		Model accuracy increases as E or E' approaches 1.0		
Baseline adjusted coefficient (Garrick), E':	0.380				
Monthly NSE	0.753				

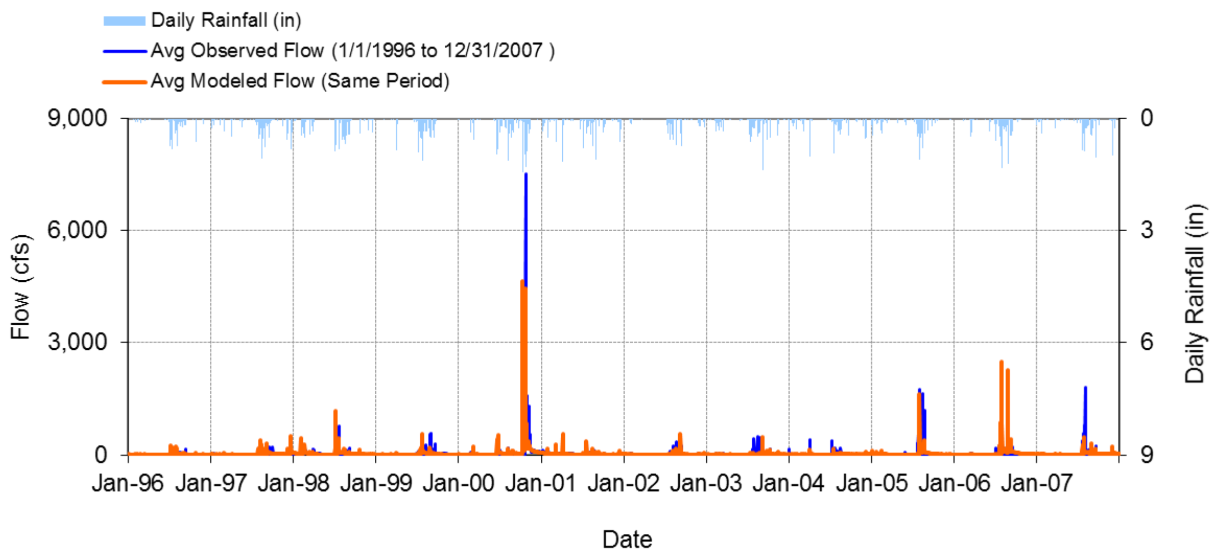

Figure A-10. Mean daily flow: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

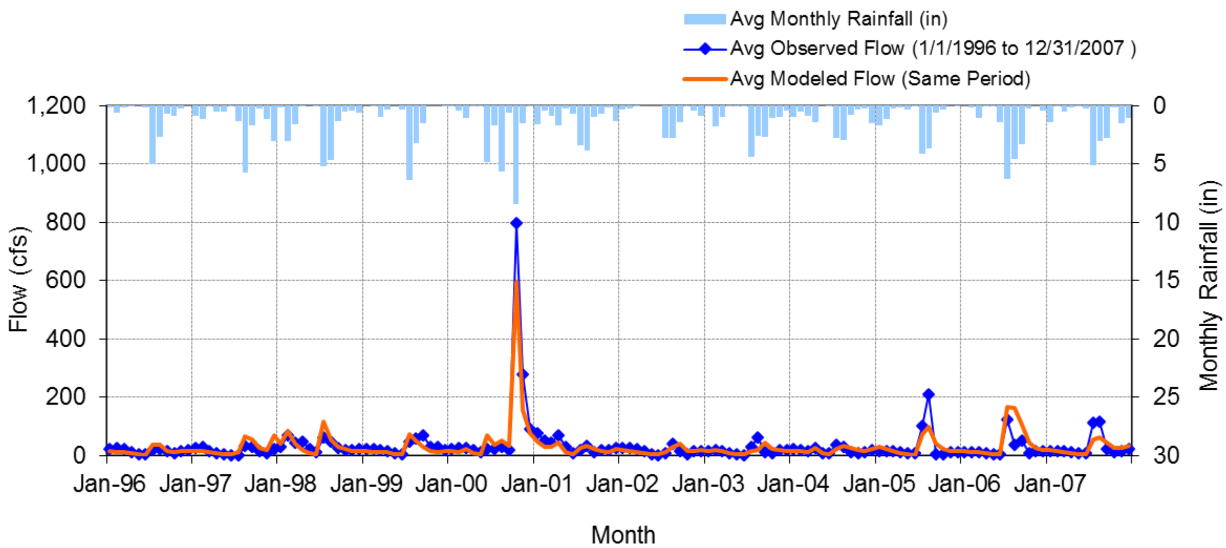

Figure A-11. Mean monthly flow: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

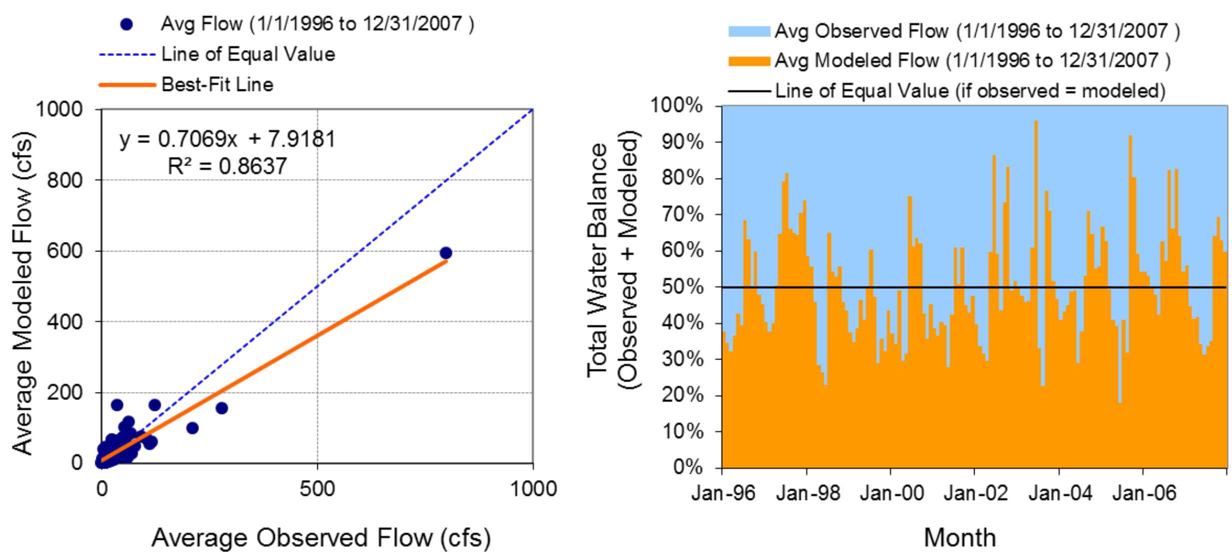

Figure A-12. Monthly flow regression and temporal variation: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

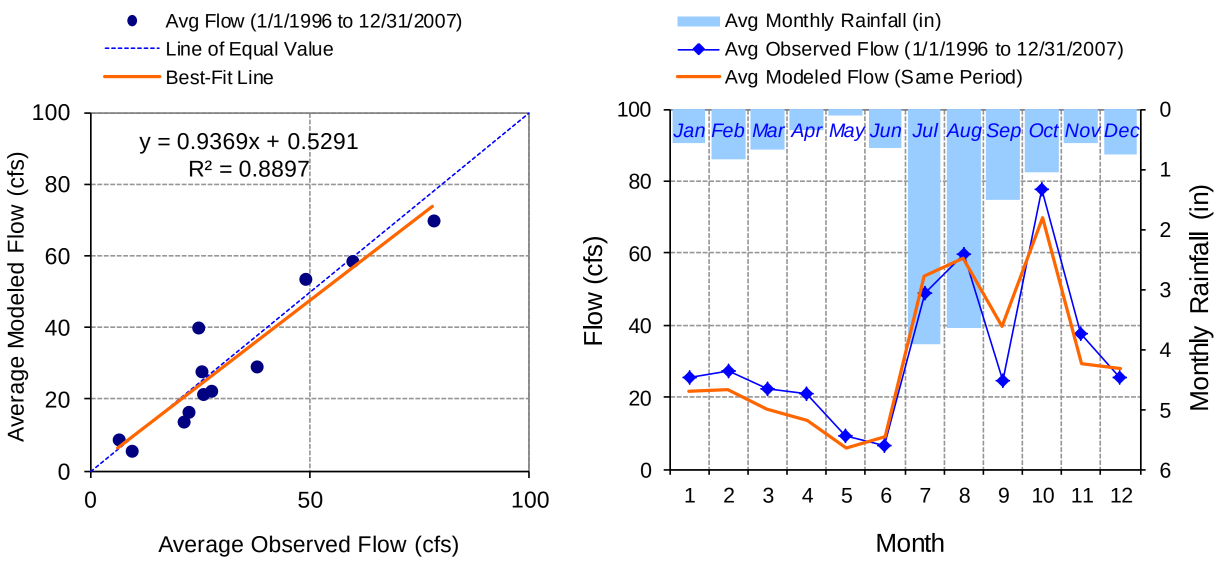

Figure A-13. Seasonal regression and temporal aggregate: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

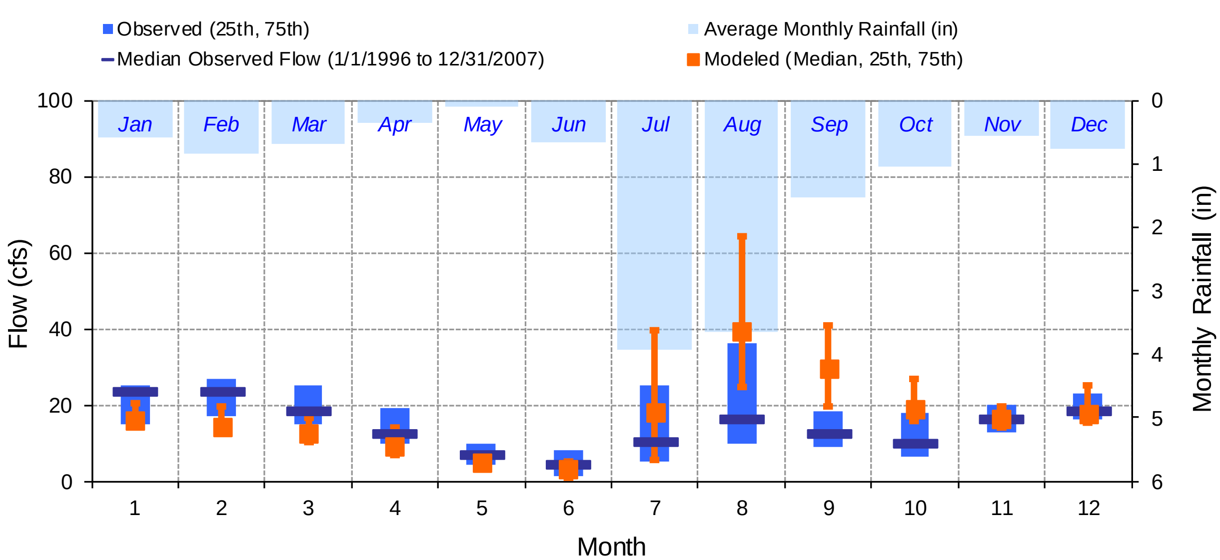

Figure A-14. Seasonal medians and ranges: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

Table A-3. Seasonal summary: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

MONTH	OBSERVED FLOW (CFS)				MODELED FLOW (CFS)			
	MEAN	MEDIAN	25TH	75TH	MEAN	MEDIAN	25TH	75TH
Jan	25.55	23.00	15.00	25.00	21.54	15.95	14.33	20.57
Feb	27.44	23.00	17.00	27.00	22.18	14.36	12.70	19.37
Mar	22.31	18.00	15.00	25.00	16.61	12.40	10.10	16.77
Apr	21.01	12.00	10.00	19.00	13.60	9.03	6.91	13.86
May	9.22	6.70	4.10	9.70	5.67	5.10	4.02	6.74
Jun	6.33	4.05	1.30	7.90	8.80	3.29	0.78	5.20
Jul	48.68	9.95	5.18	25.25	53.54	18.03	5.35	39.46
Aug	59.61	16.00	9.80	36.25	58.62	39.52	24.49	64.45
Sep	24.33	12.00	9.00	18.25	39.82	29.60	19.78	40.78
Oct	77.93	9.60	6.30	18.00	69.81	19.06	15.59	26.70
Nov	37.71	16.00	12.75	20.00	29.13	16.30	14.13	19.58
Dec	25.23	18.00	16.00	23.00	28.05	17.52	15.14	25.30

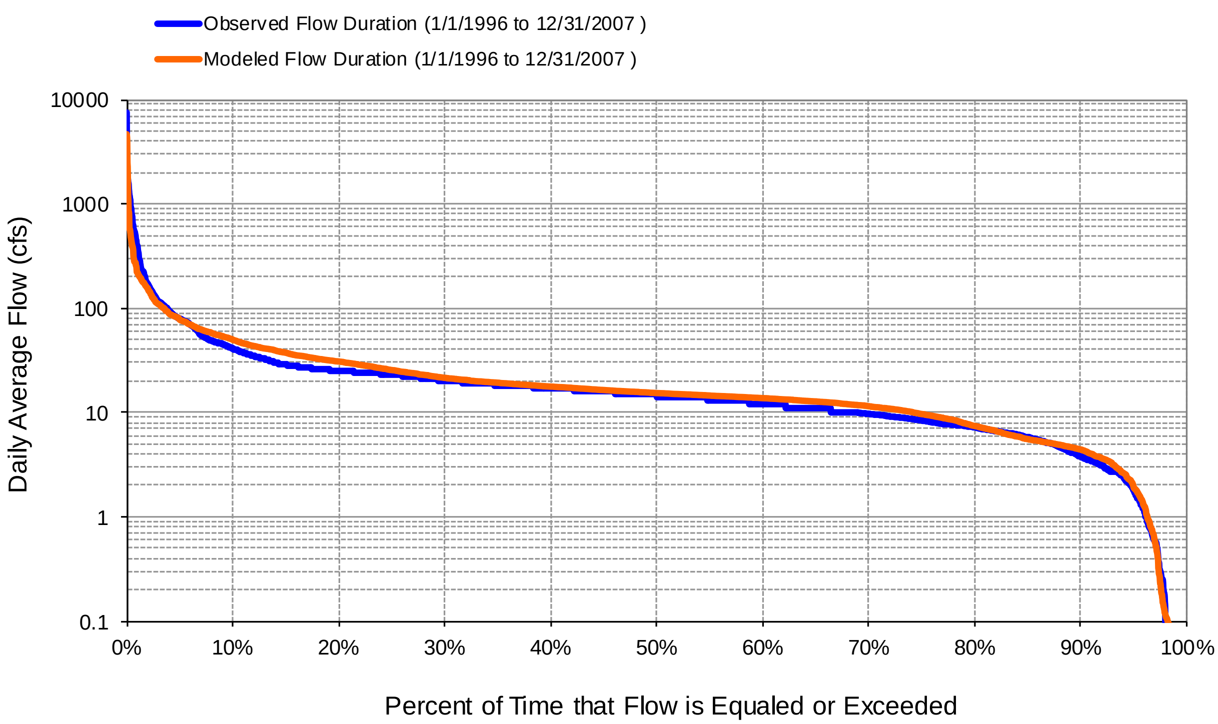

Figure A-15. Flow exceedance: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

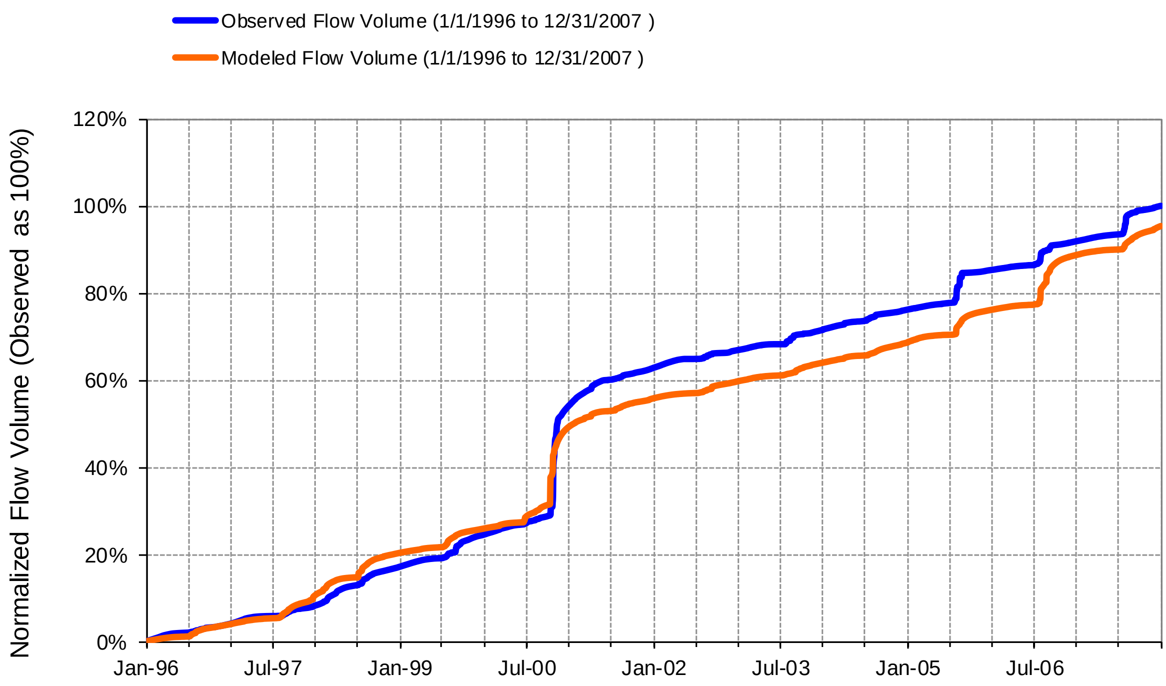

Figure A-16. Flow accumulation: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

Table A-4. Summary statistics: Model Outlet 91 vs. USGS 09481740 Santa Cruz River at Tubac, AZ.

SWAT Simulated Flow		Observed Flow Gage	
REACH OUTFLOW FROM OUTLET 91 12-Year Analysis Period: 1/1/1996 - 12/31/2007 Flow volumes are (inches/year) for upstream drainage area		USGS 09481740 Santa Cruz River at Tubac, AZ Hydrologic Unit Code: 04100011 Latitude: 31°36'46" Longitude: -111°02'27" Drainage Area (sq-mi): 1,210	
Total Simulated In-stream Flow:	**0.35**	Total Observed In-stream Flow:	**0.36**
Total of simulated highest 10% flows:	**0.18**	Total of Observed highest 10% flows:	**0.22**
Total of Simulated lowest 50% flows:	**0.05**	Total of Observed Lowest 50% flows:	**0.05**
Simulated Summer Flow Volume (months 7-9):	**0.14**	Observed Summer Flow Volume (7-9):	**0.13**
Simulated Fall Flow Volume (months 10-12):	**0.12**	Observed Fall Flow Volume (10-12):	**0.13**
Simulated Winter Flow Volume (months 1-3):	**0.06**	Observed Winter Flow Volume (1-3):	**0.07**
Simulated Spring Flow Volume (months 4-6):	**0.03**	Observed Spring Flow Volume (4-6):	**0.03**
Total Simulated Storm Volume:	**0.15**	Total Observed Storm Volume:	**0.19**
Simulated Summer Storm Volume (7-9):	**0.07**	Observed Summer Storm Volume (7-9):	**0.10**

Errors (Simulated-Observed)	*Error Statistics*	*Recommended Criteria*		
Error in total volume:	-4.62	10		
Error in 50% lowest flows:	**11.30**	**10**		
Error in 10% highest flows:	**-16.24**	**15**		
Seasonal volume error - Summer:	14.31	30		
Seasonal volume error - Fall:	-9.73 >>	30		Clear
Seasonal volume error - Winter:	-19.91	30		
Seasonal volume error - Spring:	-23.38	30		
Error in storm volumes:	-18.16	20		
Error in summer storm volumes:	-25.40	50		
Nash-Sutcliffe Coefficient of Efficiency, E:	-0.295	Model accuracy increases as E or E' approaches 1.0		
Baseline adjusted coefficient (Garrick), E':	0.118			
Monthly NSE	0.835			

3 Sediment and Bacteria Simulation

The SWAT model developed by the University of Arizona covers the entire Santa Cruz River. The water quality simulations for the USCR focus only on the portion of the model from the International Border to Sopori Wash, downstream from the city of Tubac (Figure A-17; consistent with the CWP project area).

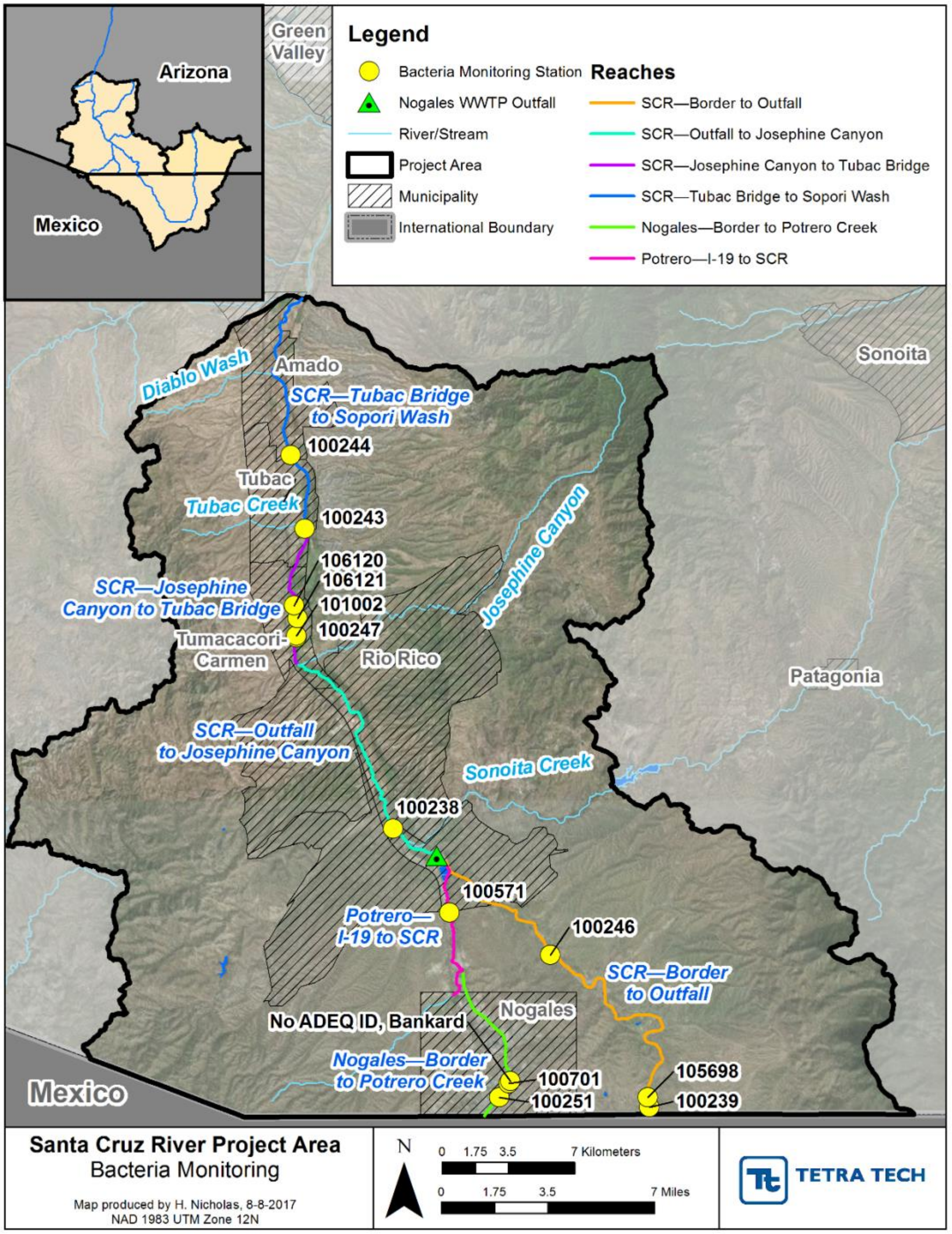

Figure A-17. USCR Project Area and Monitoring Stations.

As was noted above in Section 1, the ability of the current version of SWAT to simulate bacteria is limited. In essence the model provides an estimate of bacterial loading from manure and point sources, but does not represent urban impervious sources or re-release from the sediment. It also provides only very limited ability to calibrate instream transport of bacteria. In addition, there may well be unknown sources, such as illicit discharges, that are not included in the model. Finally, the lack of precision in the storm event simulation by the model will impair the ability to match individual observations.

Given these issues, the model is best applied in an exploratory or forensic mode. That is, the intention was to develop a model that provides a reasonable best estimate of manure and point sources of bacteria. Comparison to data should then reveal areas of consistent discrepancy, which may in turn indicate the potential for other, unmodeled sources. This exploratory analysis focused on fecal coliform bacteria and not *E. coli* because the majority of observations prior to 2010 (the end of the model simulation period based on available weather data) are for fecal coliform. While the model was calibrated based on observed fecal coliform data and literature values, model output was then converted to *E. coli* to enable bacteria loading estimates for both fecal coliform and *E. coli* (see Section 4.2).

3.1 SWAT Implementation for Sediment and Bacteria Simulation

The existing model was updated to simulate sediment and bacteria loading and transport in addition to hydrology. Sediment simulation is needed because the washoff of sediment from the land surface controls a portion of the washoff of bacteria. The instream sediment simulation is not, however, critical to the model due to SWAT's lack of representation of bacteria-sediment interactions in the channel.

3.2 Parameters for Sediment Simulation

SWAT uses the Modified Universal Soil Loss Equation (MUSLE) approach for simulating erosion from the land surface. MUSLE combines a runoff energy factor calculated from the hydrology model with USLE erosion (K), length-slope (LS), cover (C), and practice (P) factors to predict delivered sediment load at the subbasin scale. The K factor is provided in the SWAT soils database, while the LS factor is internally calculated from the DEM. The C factor was assigned from literature values appropriate to the land cover type, while the P factor is assumed to be 1.

3.3 Parameters for Bacteria Simulation

Ongoing work by researchers at the University of Arizona (T.C. McOmber, J.E. McLain, B. Rivera, and Dr. C.M. Rock) has included microbial source tracking using DNA markers for *Bacteriodes* bacteria. This genus of bacteria is found within the guts of all warm-blooded animals, as well as reptiles, birds, and fish, and can be tracked back to a source type based on specific DNA markers. Tests were conducted for human, bovine, and total bacteria species. The report was completed in 2014 (McOmber, 2014). Dr. Rock also presented a summary of the results to the Upper Santa Cruz Watershed Association in January 2014.

The microbial source tracking results help to indicate where different sources are important, but do not provide quantitative measures of loading. Notably, the marker results for human and bovine sources cannot be compared directly on a quantitative basis.

The human source marker was detected in 97 percent of the samples collected, with highest concentrations in Nogales Wash in mid-June and July (McOmber, 2014). Increases were also observed in downstream locations at this time, suggesting that the presence of human sources upstream may affect sites downstream. This study also observed a decrease in the amount of detections and the concentrations of the human marker as water flows from Nogales Wash in Mexico through the U.S., indicating little additional human inputs of bacterial loading downstream of the border. The bovine marker was detected in approximately one third of the samples. It was found at all sites, but most frequently and at the highest levels in the Santa Cruz River at Rio Rico, just downstream of the wastewater outfall, where spikes in concentration indicate loading from additional sources. This is an area where cattle grazing is known to occur. Contributions from wildlife were not analyzed by microbial source tracking (McOmber, 2014).

Based on this research, nonpoint contributions from humans (along with other urban sources), cattle, and wildlife were included in the model. The table below shows the land use classes modeled in SWAT and their associated bacteria sources (Table A-5).

Table A-5. SWAT Land Use Classes and Bacteria Sources.

SWAT Land Use	Description	Bacteria Source
AGRL	Agriculture/Pasture	Cattle
FRSD	Deciduous Forest	Wildlife
FRSE	Evergreen Forest	Wildlife
RNGB	Shrub/Scrub	Cattle, Wildlife
RNGE	Grassland/Herbaceous	Cattle, Wildlife
URBN	Urban	Human
SWRN	Barren	

3.3.1 Wildlife Sources

General wildlife input was represented based on the maximum ecological carrying capacity for mule deer, which yields a population density of 4.5 mule deer/km^2 was assumed for forested areas in the watershed (Hanson and McCulloch, 1955). Arthur and Alldredge (1980) report a daily fecal output of 391grams (g) per mule deer. Multiplying daily output by the population density yielded a manure deposition rate of 0.018 kilograms per hectare per day (kg/ha/day) for forest and chaparral/range land areas. Bacterial concentrations in herbivore manure are based on the analysis of Wang et al. (2004) for cattle (1.425×10^7 #/g of manure for fecal coliforms and 7.075×10^6 #/g of manure for *E. coli*).

3.3.2 Cattle Sources

Livestock inventory released by the United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS) Census of Agriculture for 2012, 2007, 2002, and 1997 were used to estimate the cattle population in the watershed. Table A-6 shows the cattle inventory as reported by USDA-NASS for Santa Cruz County, which can be used to approximate the cattle density in the U.S. portion of the watershed under the assumption that cattle are distributed on the pasture and agricultural land (which are combined in the model as an “agricultural” land use), and chaparral/range land areas using the average value presented in Table A-6. Using American Society of Agricultural and Biological Engineers (ASABE) standard manure production rates a cattle manure deposition rate of 4.18 kg/ha/day to relevant land areas was estimated. The agricultural/pasture lands lie along the river, so the cattle are naturally concentrated in that area; however, information was not available to more precisely determine cattle density in individual model subwatersheds. Other sources on agricultural land, such as birds, are not explicitly represented.

Table A-6. Cattle inventory for Santa Cruz County

TYPE	1997	2002	2007	2012	Average
Cattle, Cows	11,527	7,259	9,254	11,968	10,002
Cattle, Cows (beef)	11,507	7,250	0	11,951	7,677
Cattle, Cows (milk)	20	9	0	12	10
Cattle, Calves	6,004	4,334	5,204	9,209	6,188

Source: USDA-NASS

3.3.3 Human Sources

SWAT does not provide a direct mechanism for simulation of washoff of bacteria from urban impervious areas. To partially compensate for this limitation, a fecal “manure” source was assigned to the pervious fractions of the urban lands in the watershed. Bacterial accumulation rates for this area are not known, but are assumed to be 2 x 10^{10} #/ha/yr for urban land (pervious and impervious), as suggested in the EPA/BASINS Bacterial Indicator Tool (http://water.epa.gov/scitech/datait/models/basins/upload/bit.zip). This urban source is essentially a placeholder as it cannot account for loading during small storms that cause washoff primarily from impervious surfaces, nor does it account for other urban sources such as illicit discharges, failing septic systems, leaky sewers, and trash disposal. These other sources will presumably be part of the difference between model output and observed loads.

The University of Arizona SWAT model includes discharges from the Nogales International Wastewater Treatment Plant (NIWTP), but specified at a constant average flow rate. Monthly monitoring reports for 2001-2007 on the EPA ICIS system reveal that the fecal coliform concentrations in the discharge were highly variable during this time period, with an average monthly geometric mean value of 20.1 #/100 ml and a maximum of 2,400 #/100 ml. Sanders et al. (2013) report an average of 41.6 and a maximum of 229, but do not state the period analyzed. The high variability of concentrations made it infeasible to estimate a daily load time series for the effluent; therefore, a fecal coliform concentration of 146 #/100 ml was assigned to the discharge, which approximates the 99th percentile of monthly geometric mean values and the 80th percentile of daily maximum values. Use of this value provides an upper boundary, above which, output concentrations are unlikely to be attributable to the NIWTP. Because this is believed to be greater than the actual load produced by the NIWTP the discharge is not enumerated in the loading summaries. Note, however, that the assumed load from the NIWTP constitute only 0.00011 percent of the total annual load at Tubac, so this assumption does not bias the model evaluation of load sources.

The NIWTP did not report *E. coli* concentrations, so these are assumed to be approximately 77 percent of fecal coliform concentrations, based on the summary of Garcia-Armisen et al. (2007). The assumption of constant load from the NIWTP imposed by the model will result in a constant predicted concentration in the river during effluent-dominated flow periods, which is at odds with observed data. However, the model contains no other sources of load during dry weather, so the test is really to examine responses when the NIWTP does not dominate conditions. In addition, because SWAT allows only a single decay rate, the influence of excess chlorine in portions of the stream network cannot be fully represented. These data, and the model simulation time period, do not reflect the NIWTP upgrades in June 2009 as most of the instream data used for bacteria calibration were collected before these upgrades occurred.

4 Model Application

Total suspended sediment (TSS) data are limited; however, a comparison of model to data is possible at the Santa Cruz River at Chaves Siding Rd. station, which is located on the SCR – Tubac Bridge to Sopori Wash reach. Sufficient bacterial data are available coincident with the time frame of the SWAT model simulation for meaningful model-data comparisons at seven locations for fecal coliform data (see Figure A-17 above): Santa Cruz River north of Chaves Siding Road near Tubac (ADEQ 100244; on SCR – Tubac Bridge to Sopori Wash), Santa Cruz River at Santa Gertrudis Lane (100247; on SCR – Josephine Canyon to Tubac Bridge), Santa Cruz River at Rio Rico (100238; on SCR – Outfall to Josephine Canyon), Santa Cruz River at Guavai Ranch (100246; on SCR – Border to Outfall), Santa Cruz River at International Border (100239; on SCR – Border to Outfall), Potrero Creek at Ruby Road (100571; on Potrero – I-19 to SCR), and Nogales Wash at Morley Street Tunnel (100251; on Nogales – Border to Potrero Creek). Smaller amounts of *E. coli* data are also available at these stations, except for Guavai Ranch. In addition, there has been intensive monitoring for *E. coli* since 2008 for Nogales Wash South of Rt. 82 overpass (100701; on Nogales – Border to Potrero Creek). The downstream station near Tubac has the greatest amount of data during the simulation and is also approximately coincident with the USGS flow gage at Tubac, allowing calculation of loads. The Nogales Wash station monitors the important load source from Nogales, Sonora, but did not have a working flow gage during the model application period.

4.1 Sediment Simulation

Only limited observations of TSS are available from the Santa Cruz River project area during the model simulation period. Further, observed TSS depends to a large extent on channel transport, scour, and deposition processes, and so does not provide a particularly strong constraint on the upland erosion simulation when only scattered observations are available. Therefore, the model comparison to instream TSS is primarily a qualitative test of reasonable consistency.

For the model simulation period, the best set of TSS observations is at Tubac, but these consist of only 43 samples from 1995-1997 and 2009-2010. As shown in Figure A-18 and Figure A-19, simulations and observations are reasonably consistent for this small data set.

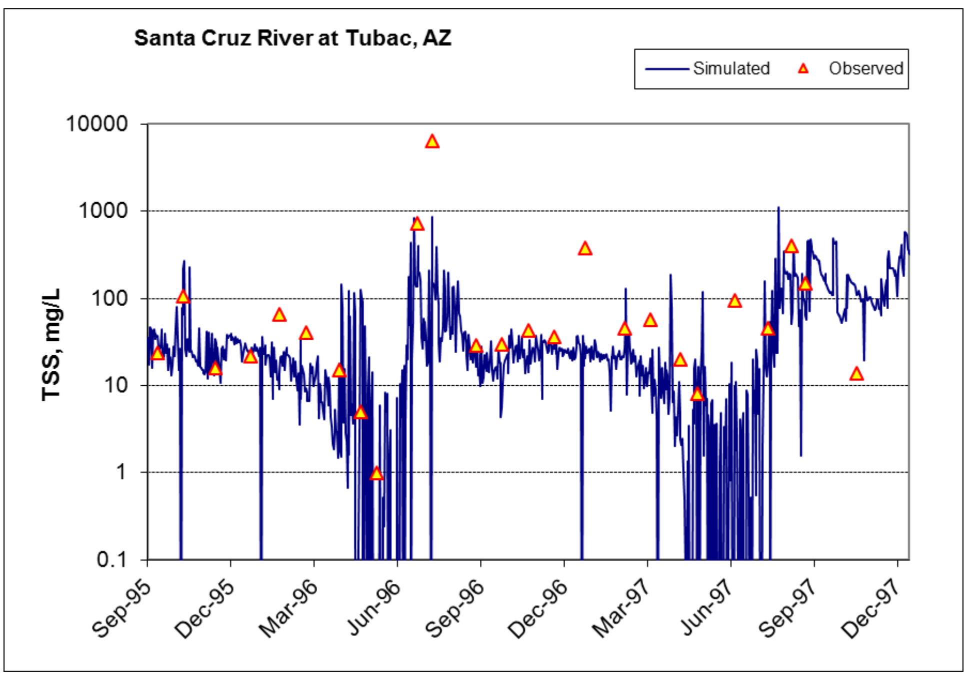

Figure A-18. TSS Simulation, Santa Cruz River at Chaves Siding Road near Tubac (100244), 1995-2000.

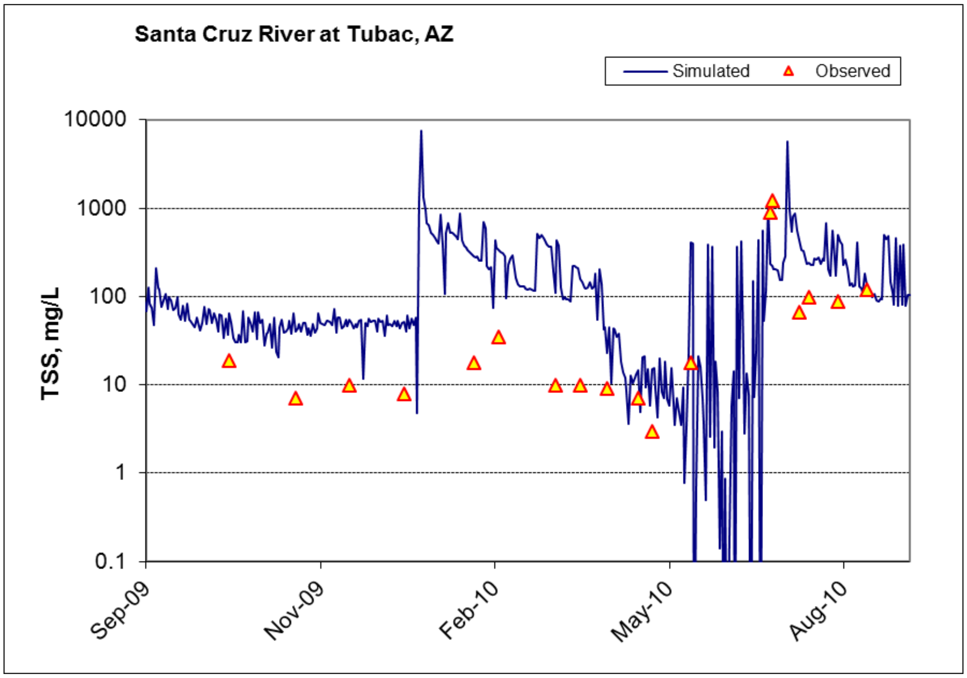

Figure A-19. TSS Simulation, Santa Cruz River at Chaves Siding Road near Tubac (100244), 2006-2010.

4.2 Bacteria Simulation

Model comparisons to observed bacteria data were performed at the eight stations mentioned above. The results are discussed in downstream to upstream order, presenting the more numerous fecal coliform data first, followed by the *E. coli* results. Although *E. coli* is the target fecal indicator bacteria in the CWP, the greater availability of observed fecal coliform results and literature values associated with nonpoint bacteria sources provided a more accurate base for bacteria simulation. *E. coli* concentrations are assumed to be 77 percent of fecal coliform concentrations, based on the summary of Garcia-Armisen et al. (2007). The model was calibrated based on observed fecal coliform data and literature values. The model output was then converted to *E. coli* to enable bacteria loading estimates for both fecal coliform and *E. coli*.

The most downstream station with extensive data (Santa Cruz River north of Chavez Siding Road) is approximately coincident with the USGS Tubac gage and thus both concentrations and loads can be evaluated at this location. Plots of observed and predicted fecal coliform concentration (Figure A-20 and Figure A-21) show that model predictions generally cover the same range as observations and are often greater than observations. A “floor” in the simulated concentrations (around 100 #/ml after decay in the reaches below the discharge) is predicted because of the assumptions for loads from the NIWTP (based on a constant flow and concentration assigned to the effluent [Section 3.3]). Observed fecal coliform concentrations lower than this “floor” likely represent conditions when the NIWTP effluent contributed significantly lower bacterial loads than the estimated constant loads used as inputs to the model.

Because there is flow gaging nearby at Tubac, the concentration observations can be converted to loads. Figure A-22 shows a log-log powerplot for observed and simulated daily loads versus daily average flow (the “observed” loads are approximations as they are based on instantaneous concentrations combined with daily average flows). Figure A-23 shows a similar plot for concentration versus flow. The multi-point cluster of simulated (blue) points at the bottom of Figure A-22 represents the constant load assumption for the NIWTP. It is primarily observations in excess of this load that are of interest to this CWP. For paired data, the average simulated load was 2.67 x 10^9 #/day, while the observed load (assuming the grab samples represent a daily average concentration) was 3.85 x 10^9 #/day. The under-estimation could be mostly due to imprecisions in daily flow simulation. Figure A-24 through Figure A-26 show the limited *E coli* samples observed at this station.

Overall, the model results and observations suggest that the model predicts a similar spread of concentrations as are seen in the observed measurements, despite uncertainties in the flow simulation. In general, the predicted model maximum may be on the high side relative to observations.

The Santa Gertrudis Lane station is also evaluated against Tubac flows, as there are no major inflows between this station and Tubac (Figure A-27 through Figure A-33). Results are similar to the downstream station on Santa Cruz River north of Chaves Siding Road.

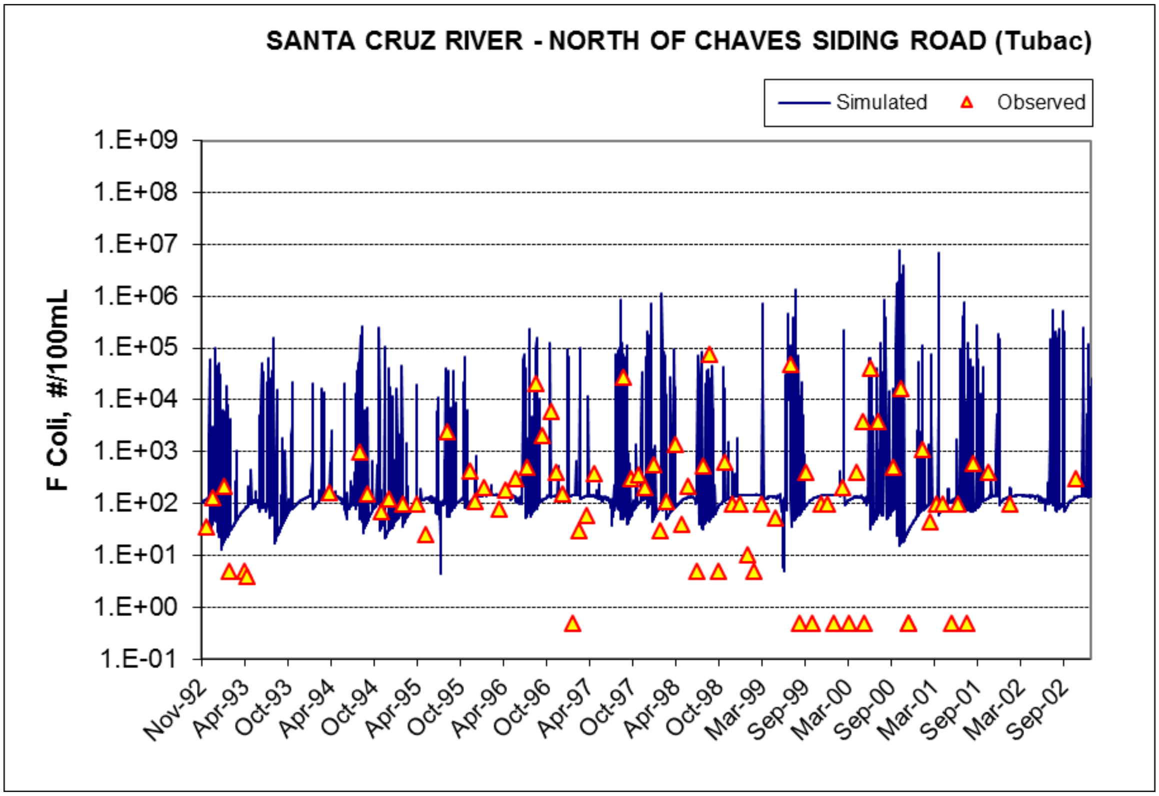

Figure A-20. Fecal Coliform Simulation, Santa Cruz River at Chaves Siding Road (100244), 1992-2002.

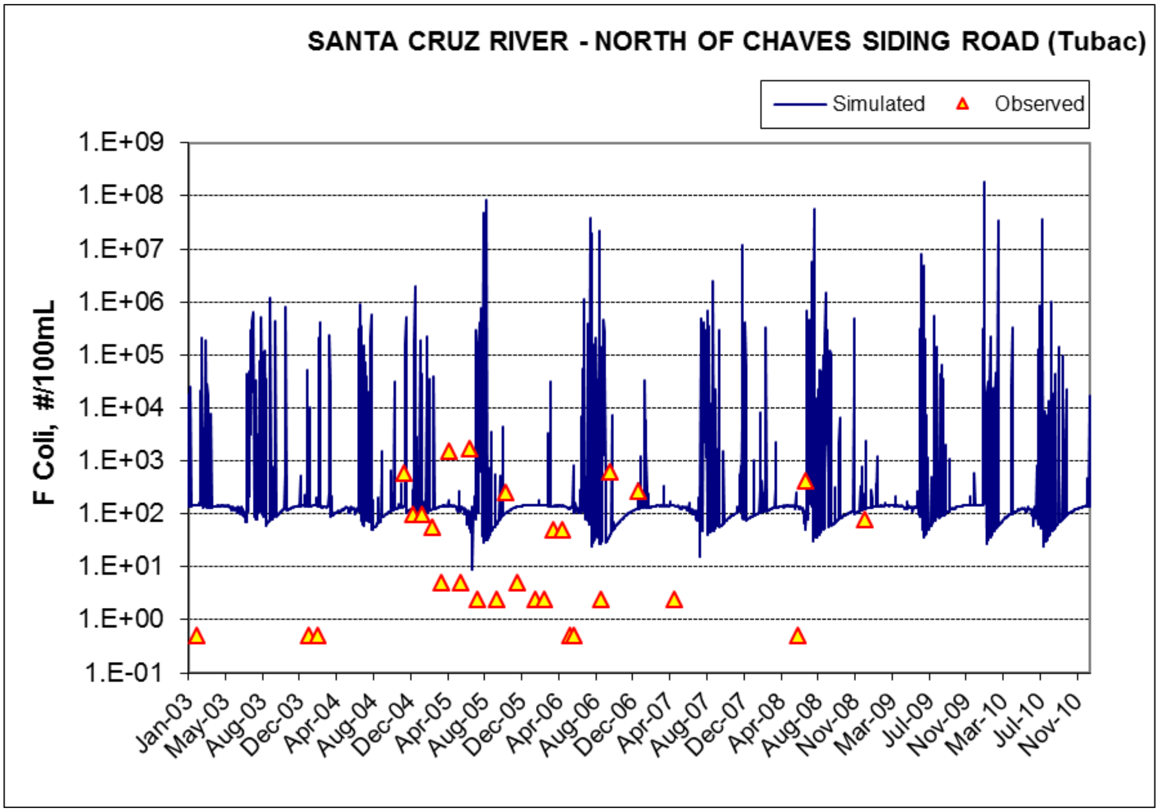

Figure A-21. Fecal Coliform Simulation, Santa Cruz River at Chaves Siding Road (100244), 2003-2010.

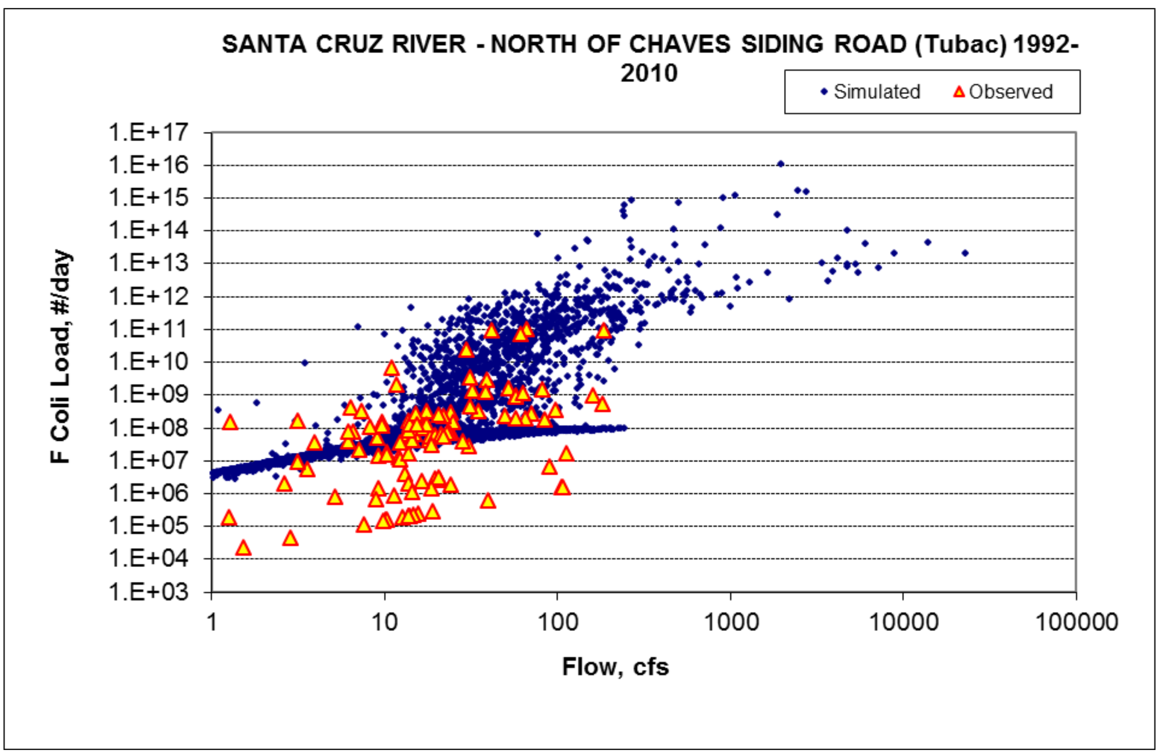

Figure A-22. Fecal Coliform Load Power Plot, Santa Cruz River at Chaves Siding Road (100244).
Note: Flows at Tubac gage for 1996 on; flows prior to 1996 are as simulated by SWAT.

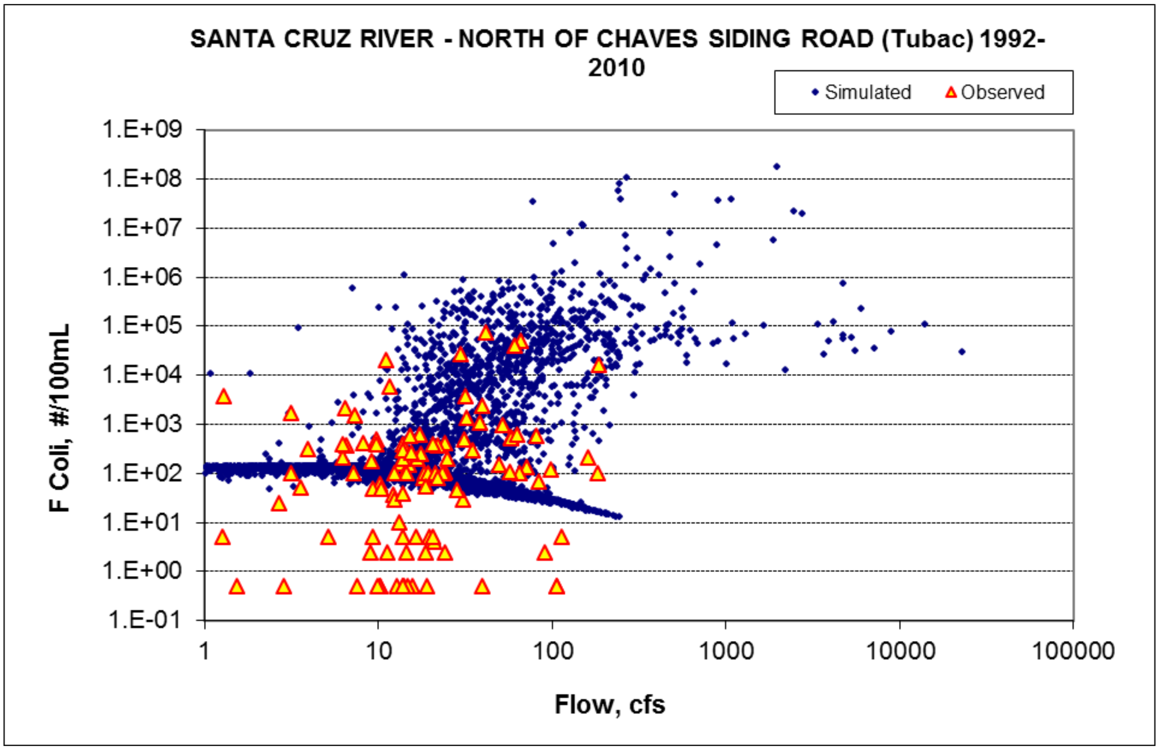

Figure A-23. Fecal Coliform Concentration Power Plot, Santa Cruz River at Chaves Siding Road (100244).
Note: Flows at Tubac gage for 1996 on; flows prior to 1996 are as simulated by SWAT.

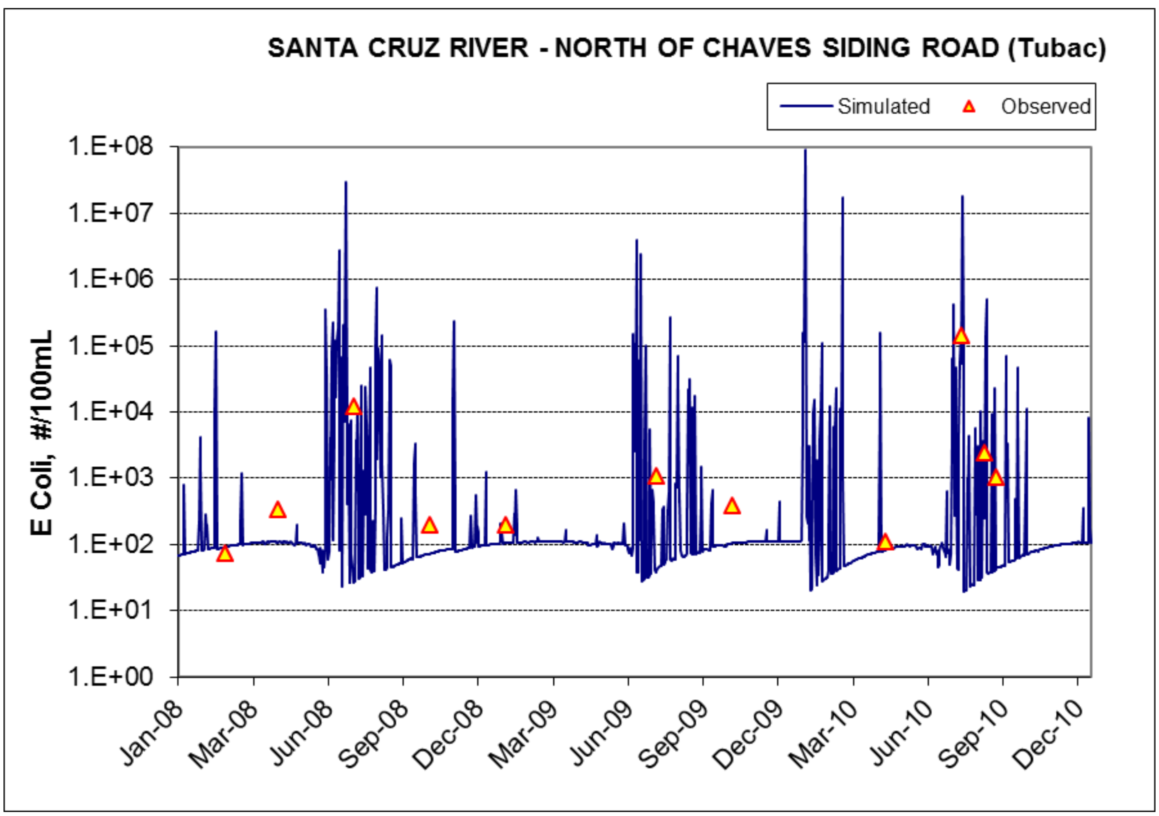

Figure A-24. *E. coli* Simulation, Santa Cruz River at Chaves Siding Road (100244), 2008-2010.

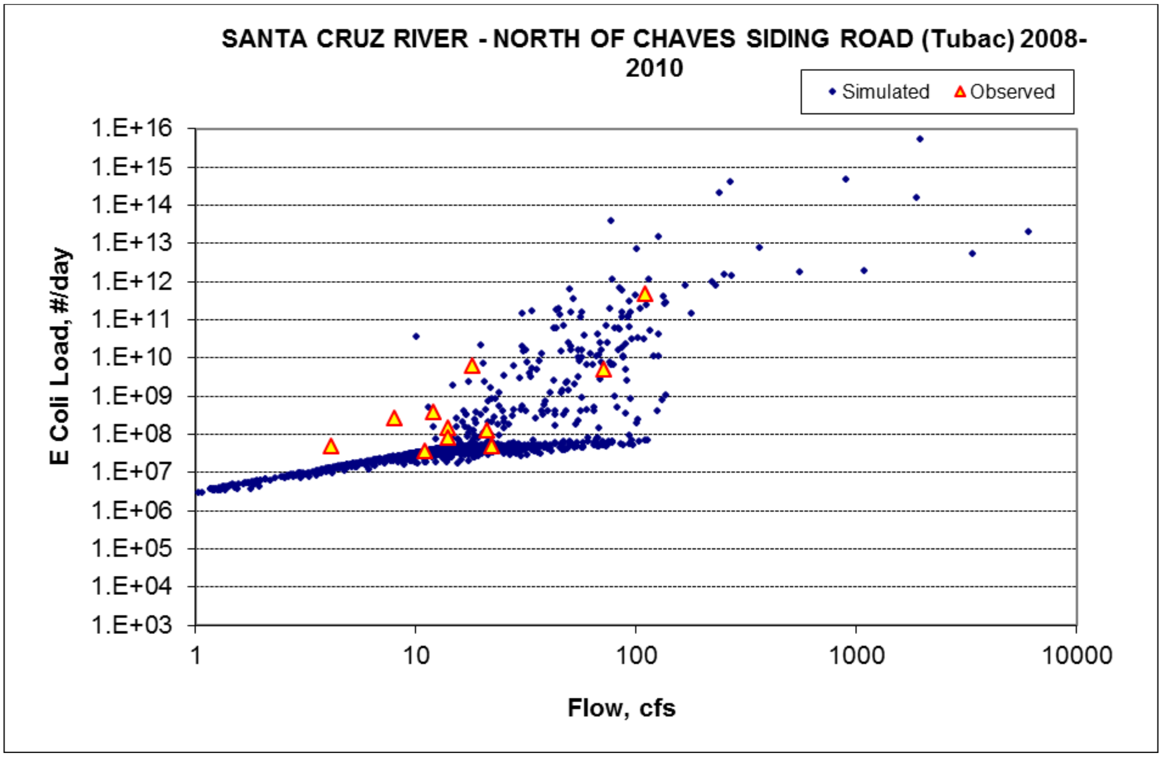

Figure A-25. ***E. coli*** **Load Power Plot, Santa Cruz River at Chaves Siding Road (100244).**

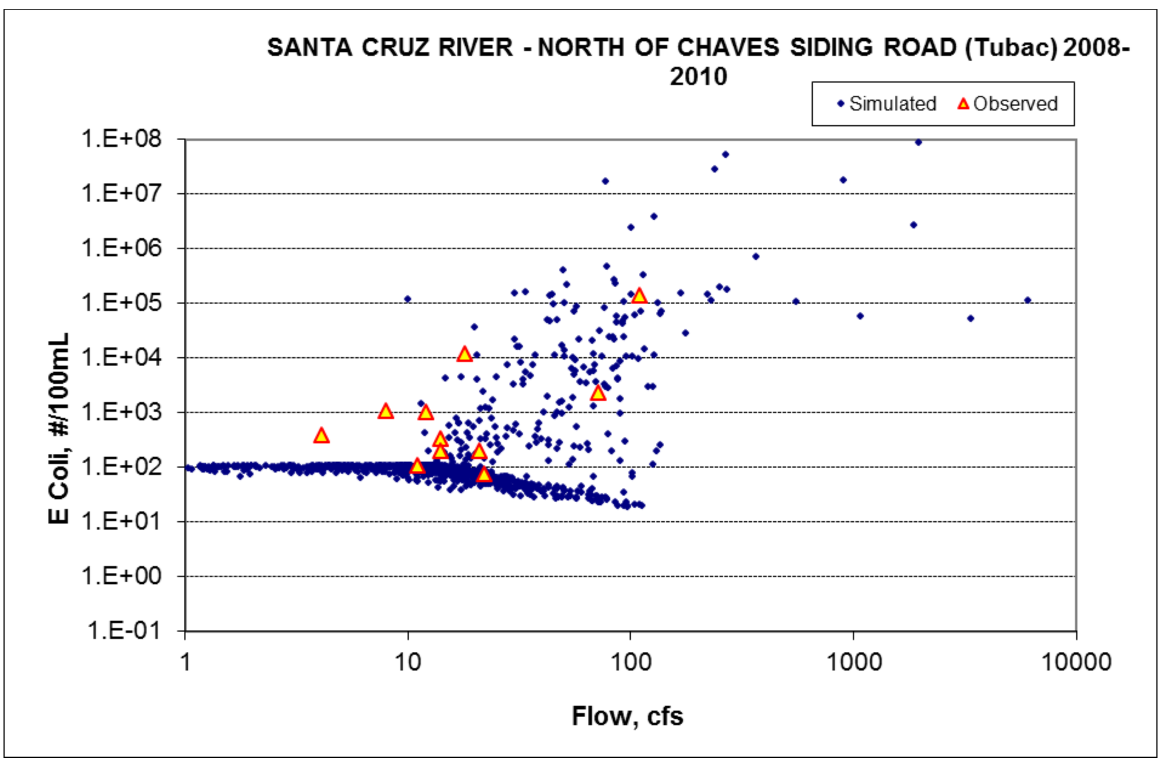

Figure A-26. ***E. coli*** **Concentration Power Plot, Santa Cruz River at Chaves Siding Road (100244).**

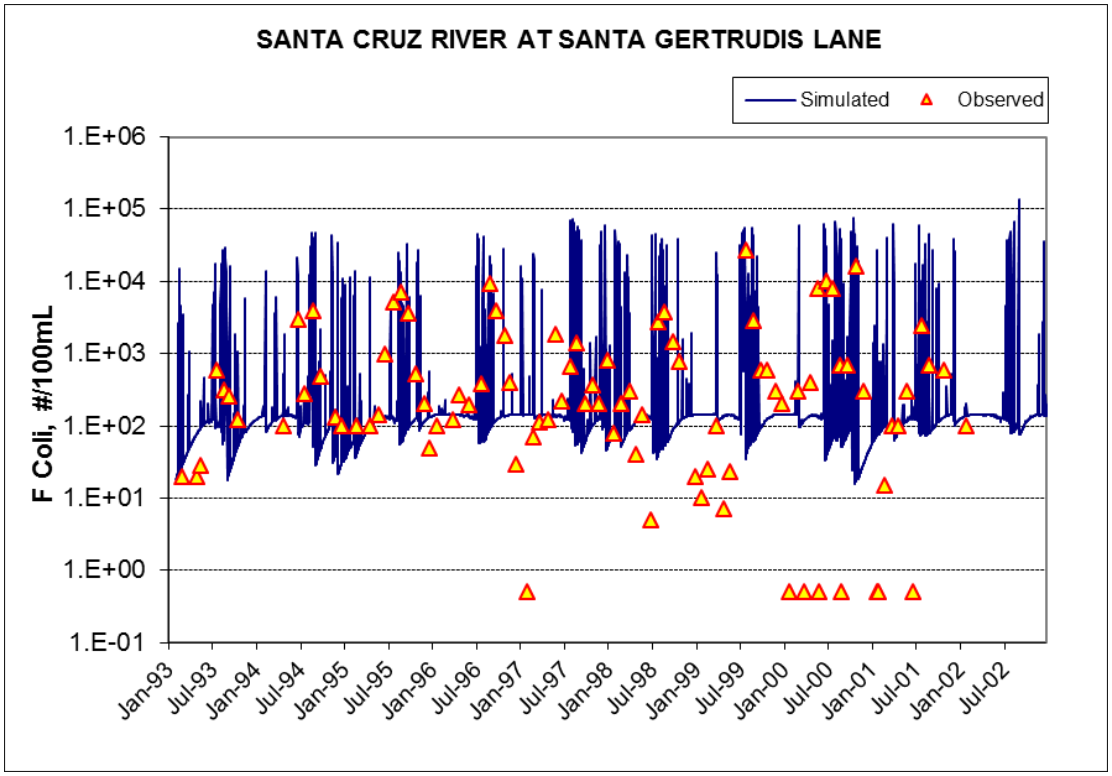

Figure A-27. Fecal Coliform Simulation, Santa Cruz River at Santa Gertrudis Lane (100247), 1993-2002.

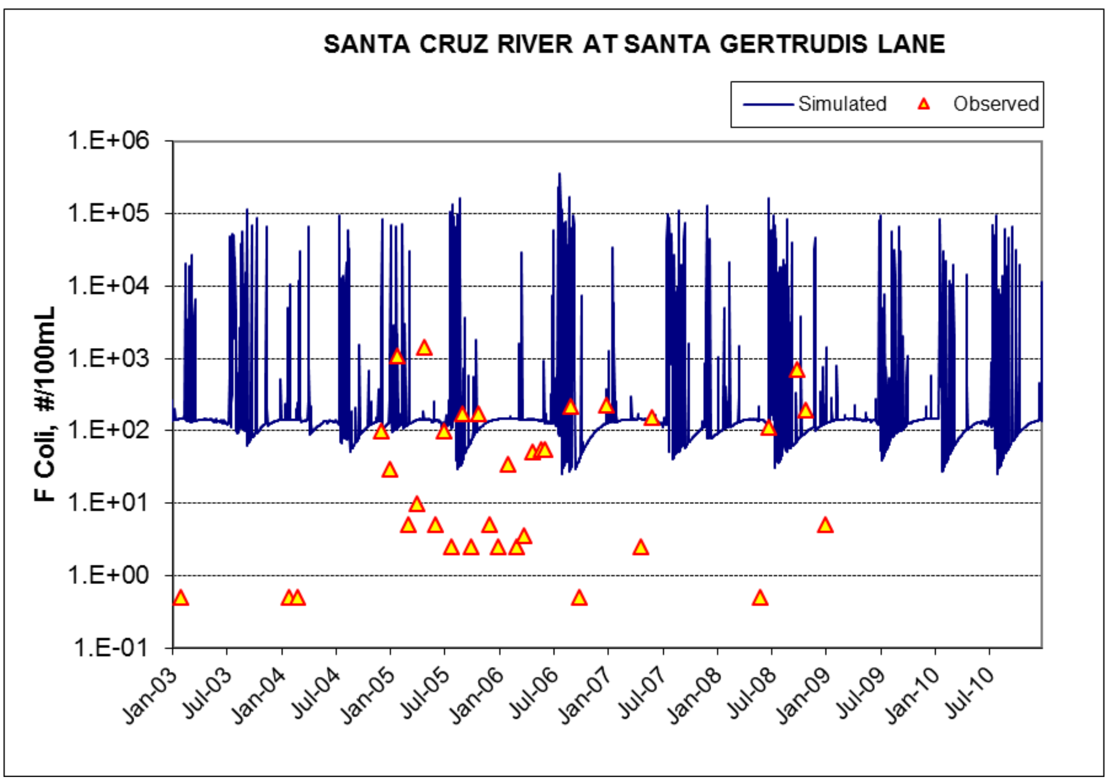

Figure A-28. Fecal Coliform Simulation, Santa Cruz River at Santa Gertrudis Lane (100247), 2003-2010.

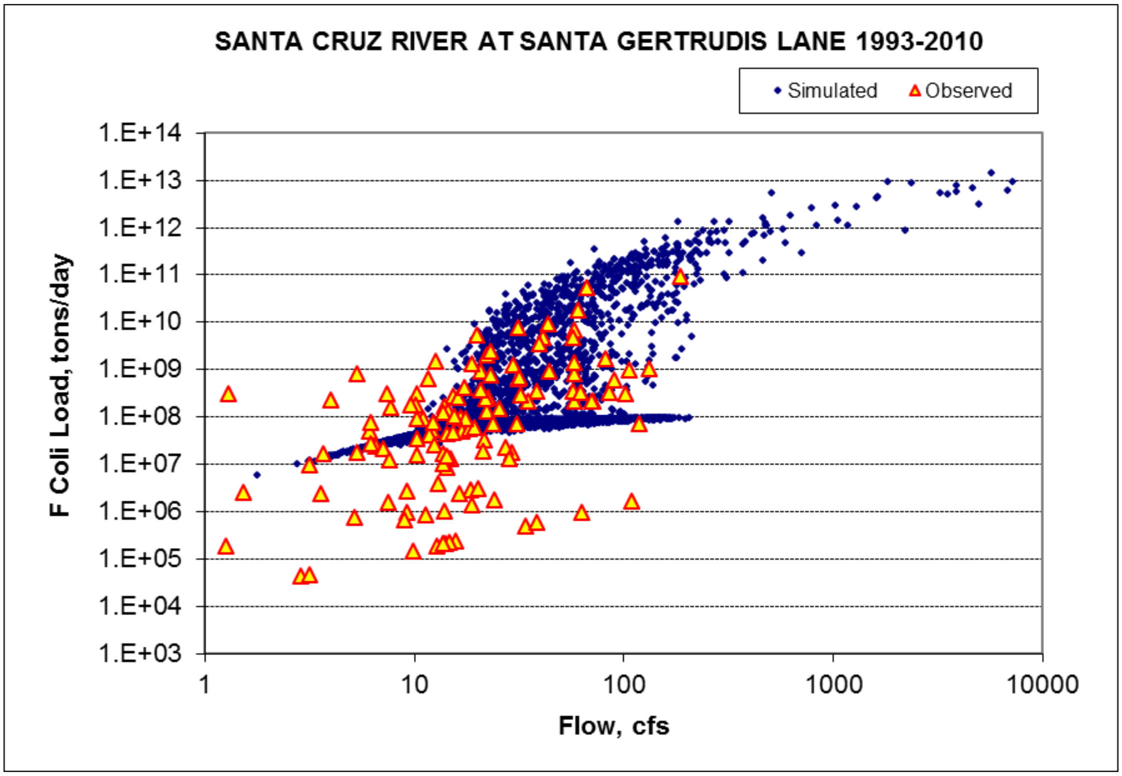

Figure A-29. Fecal Coliform Load Power Plot, Santa Cruz River at Santa Gertrudis Lane (100247).
Note: Flows at Tubac gage for 1996 on; flows prior to 1996 are as simulated by SWAT.

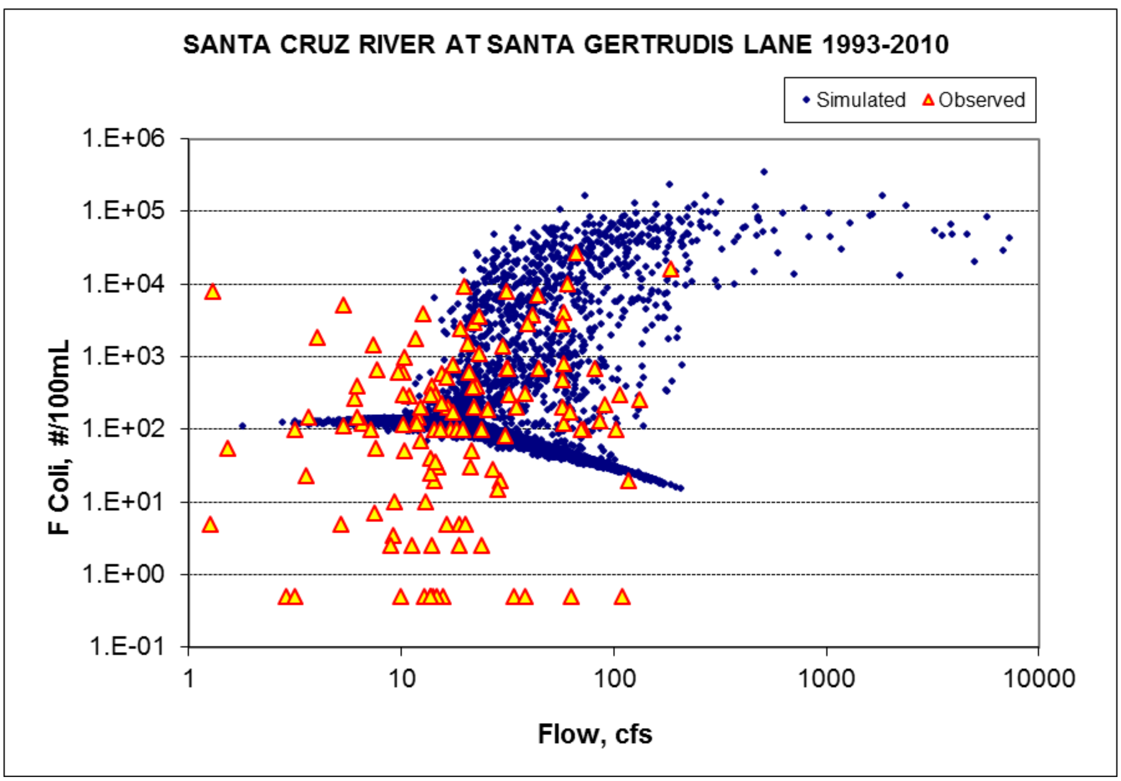

Figure A-30. Fecal Coliform Concentration Power Plot, Santa Cruz River at Santa Gertrudis Lane (100247).
Note: Flows at Tubac gage for 1996 on; flows prior to 1996 are as simulated by SWAT.

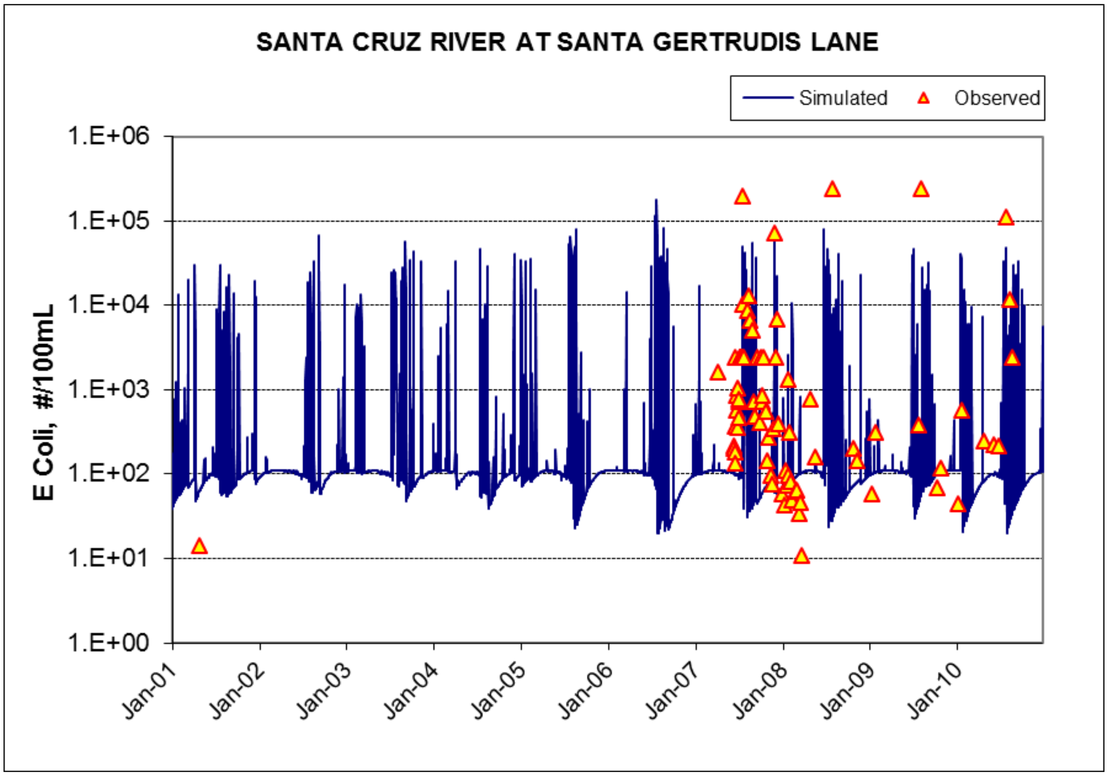

Figure A-31. *E. coli* Simulation, Santa Cruz River at Santa Gertrudis Lane (100247), 2001-2010.

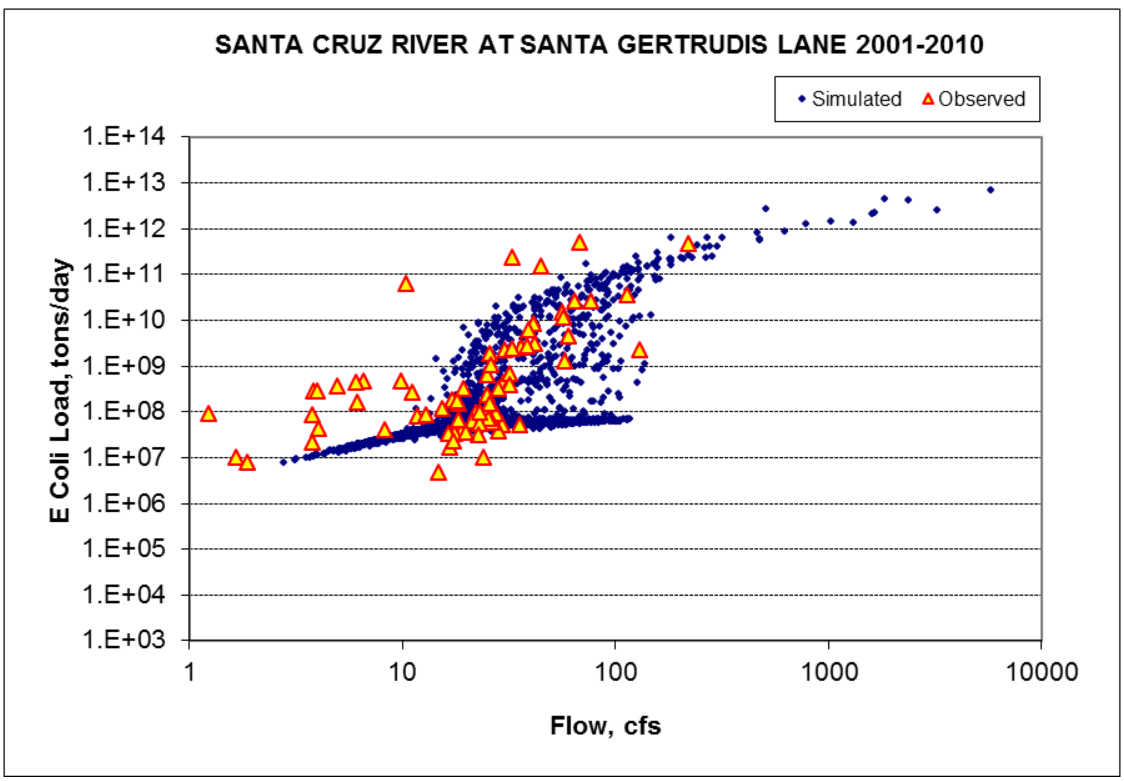

Figure A-32. *E. coli* Load Power Plot, Santa Cruz River at Santa Gertrudis Lane (100247).
Note: Flows at Tubac gage.

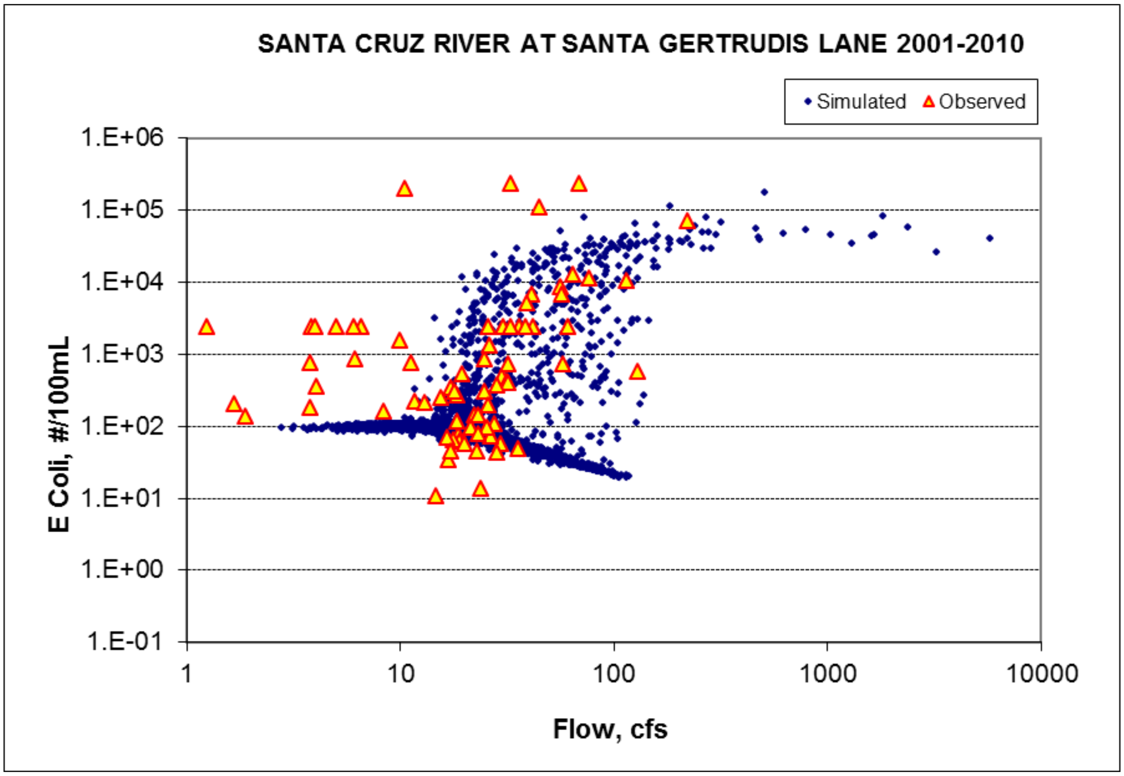

Figure A-33. *E. coli* Concentration Power Plot, Santa Cruz River at Santa Gertrudis Lane (100247).
Note: Flows at Tubac gage.

For the stations on the mainstem at Rio Rico (100238) and Guavai Ranch (100246) there are no flow gages and, as noted above, daily flow predictions from the model are not reliable; thus only concentration comparisons are possible (Figure A-34 through Figure A-37). At Rio Rico, the overall fit is strongly influenced by the assumptions regarding the NIWTP, with less instream reduction occurring at this station than at the downstream stations. The station at Guavai Ranch (Figure A-37) is upstream of the NIWTP, so the constant load associated with the NIWTP is not present. The model does a reasonable job of predicting the range of observed concentrations, although many individual observations are missed. Most notably, the model predicts zero concentrations during dry weather periods, which is not consistent with observations, likely because SWAT does not allow for association of a bacterial load with groundwater discharge.

A flow gage is also present at the International Border station on the USCR (100239), so load comparisons can be made. This station has little urban land upstream and flows are often very low. Results at this station (Figure A-38 through Figure A-44) again show that the model projects peak concentrations and loads consistent with the range of observations; however, the model does not predict dry-weather low flow concentrations observed at this station. In terms of delivered load, model over-predicts based on paired data (likely linked to imprecisions in daily flow simulation). The model predicts an average daily load of 4.46 x 10^8 #/day versus an observed estimate of 1.23 x 10^8 #/day.

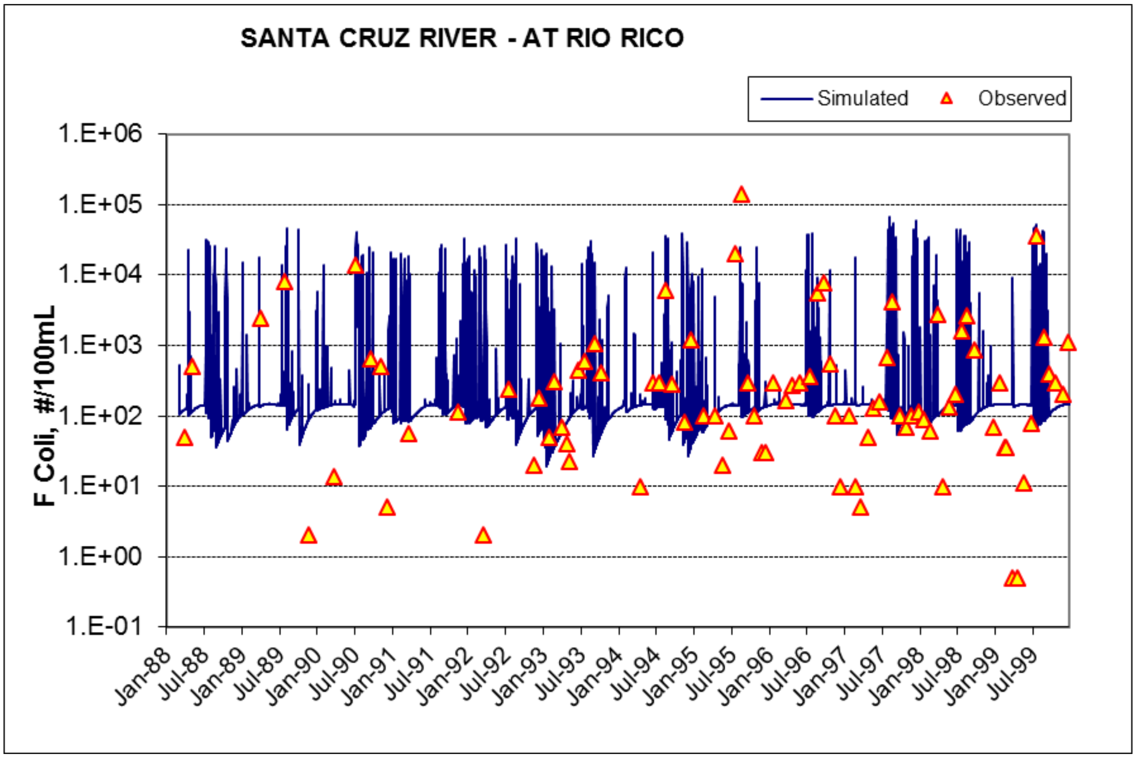

Figure A-34. Fecal Coliform Simulation, Santa Cruz River at Rio Rico (100238), 1988-1999.

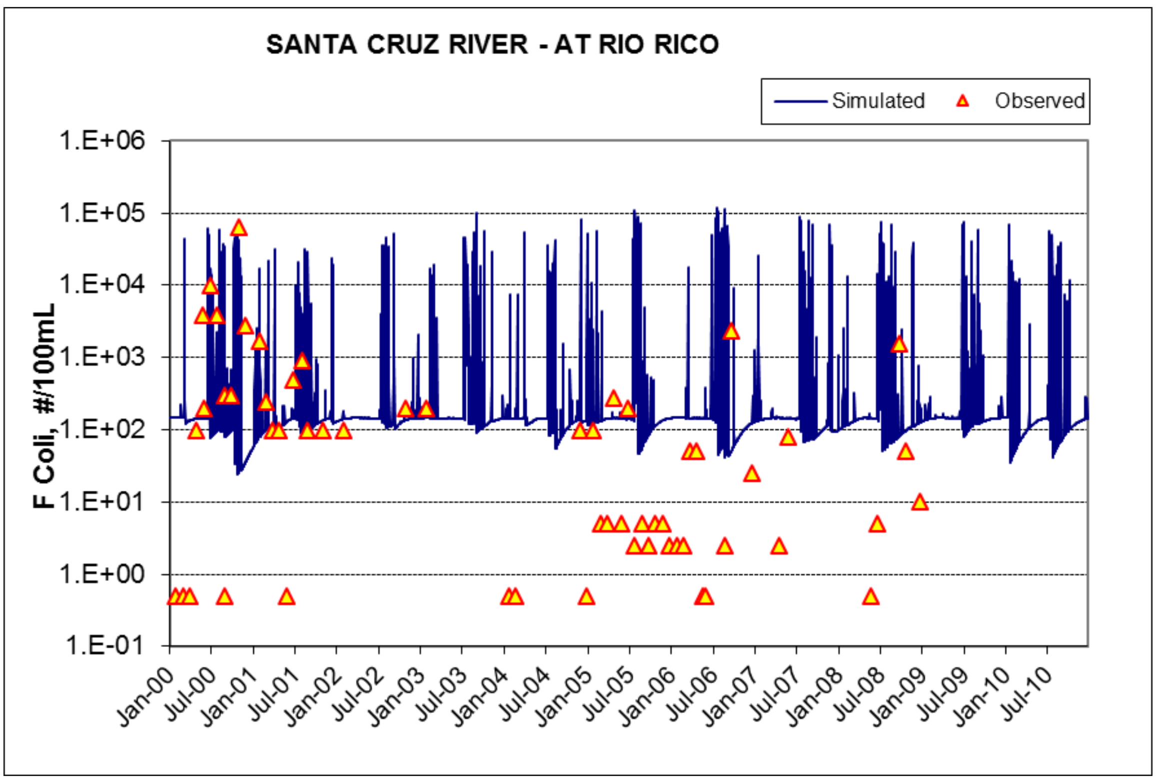

Figure A-35. Fecal Coliform Simulation, Santa Cruz River at Rio Rico (100238), 2000-2010.

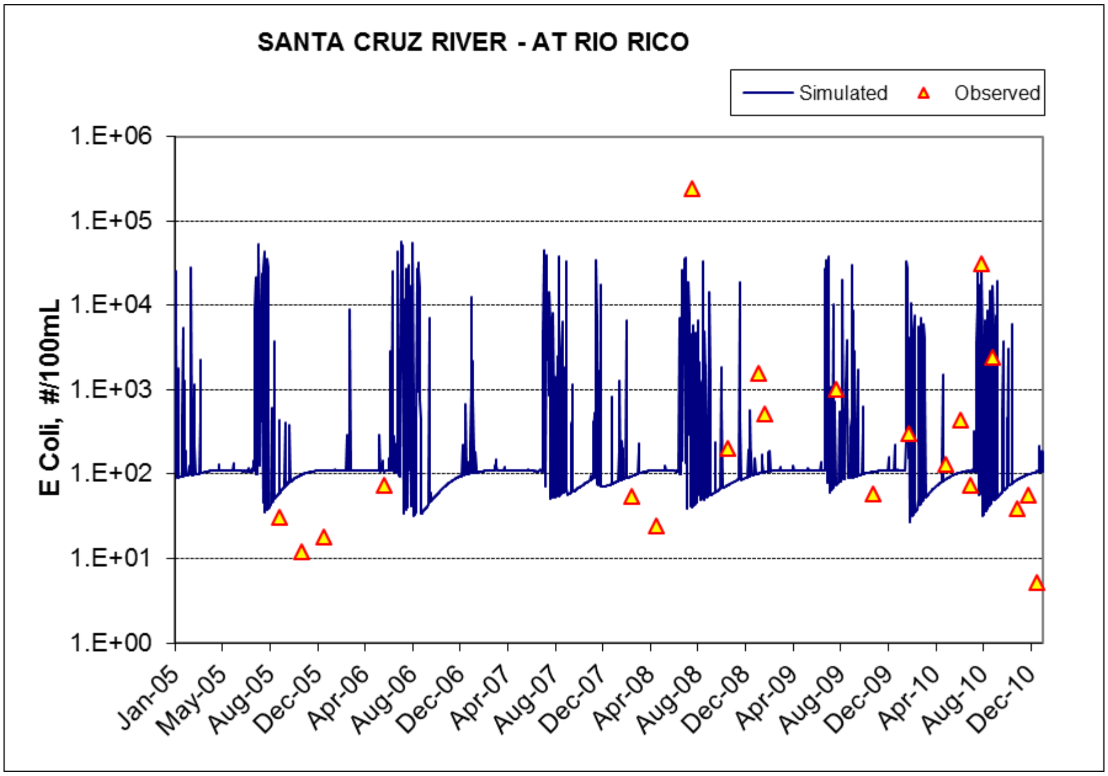

Figure A-36. ***E. coli*** **Simulation, Santa Cruz River at Rio Rico (100238), 2005-2010.**

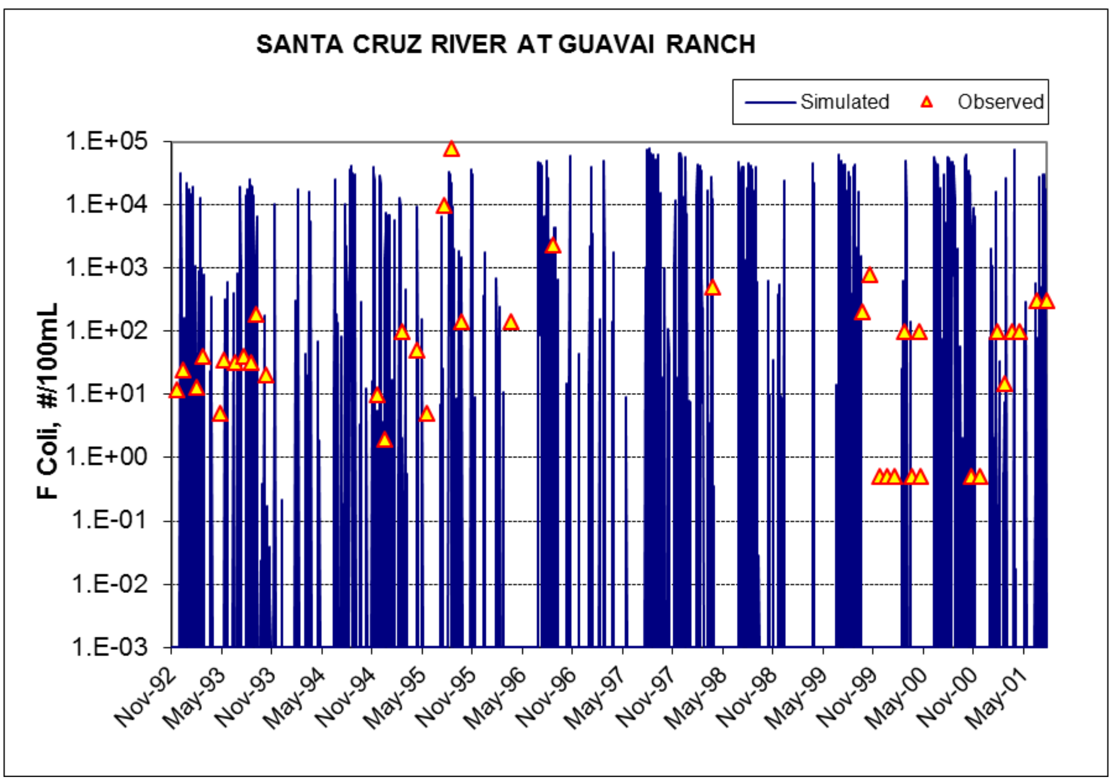

Figure A-37. Fecal Coliform Simulation, Santa Cruz River at Guavai Ranch (100246), 1992-2002.

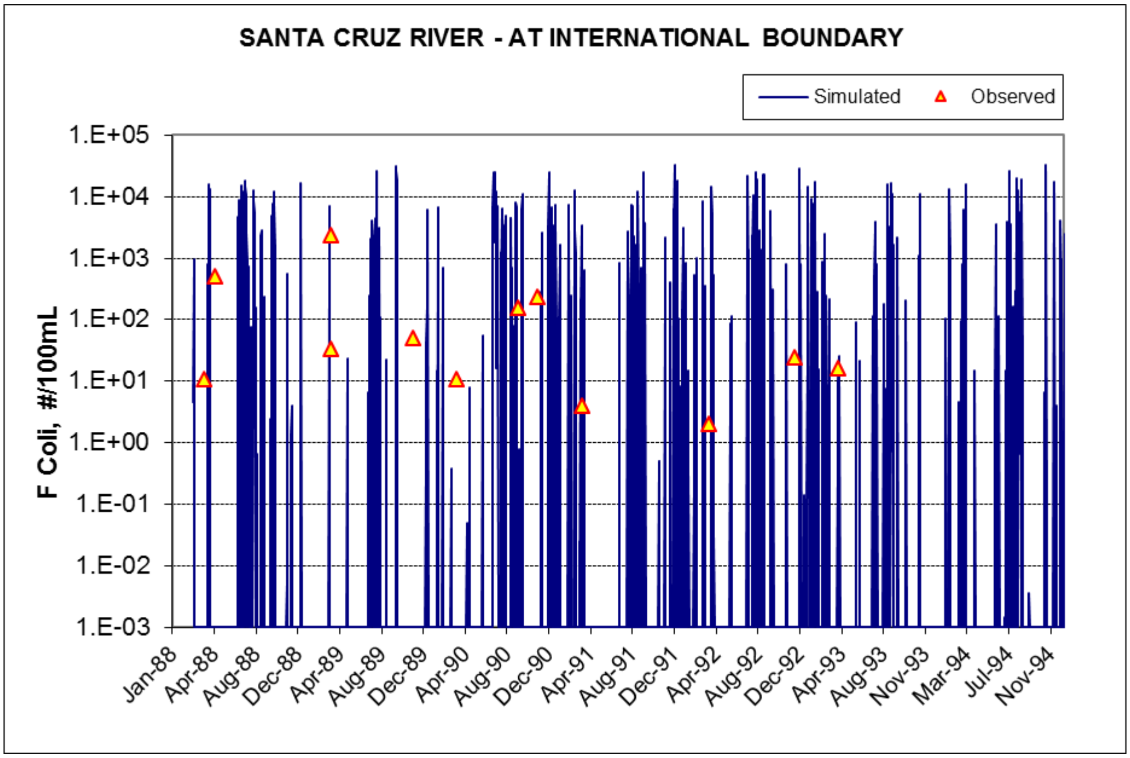

Figure A-38. Fecal Coliform Simulation, Santa Cruz River at International Border (100239), 1988-1994.

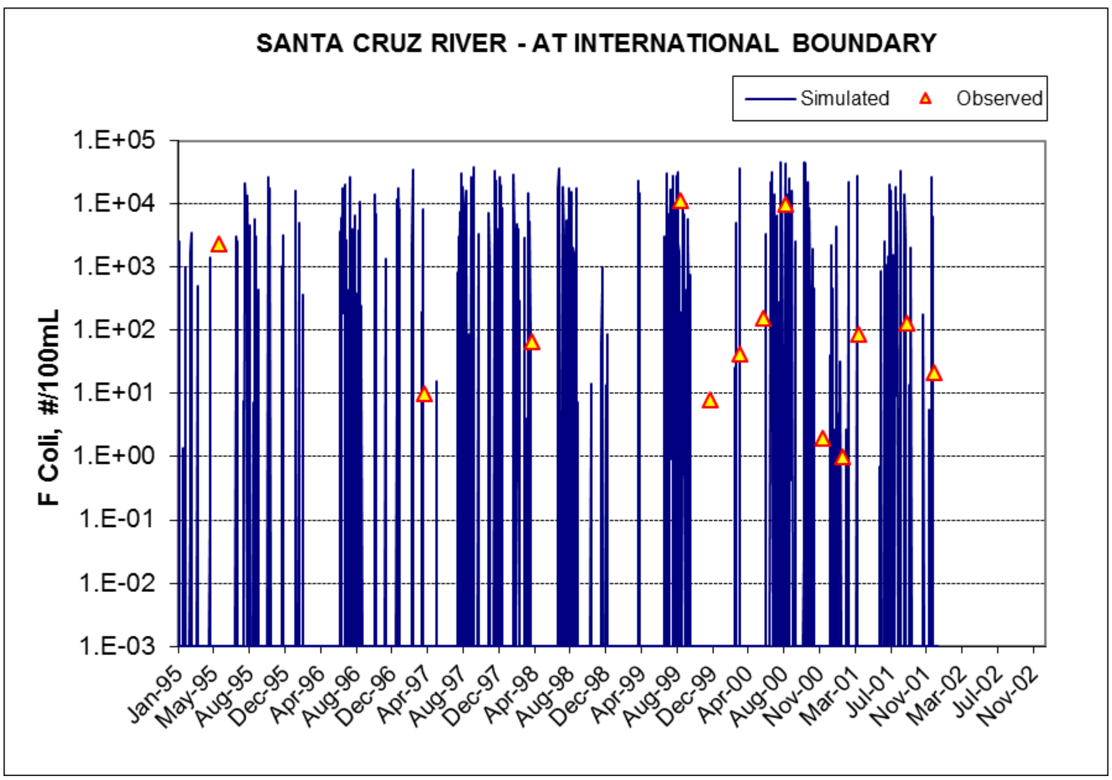

Figure A-39. Fecal Coliform Simulation, Santa Cruz River at International Border (100239), 1995-2001.

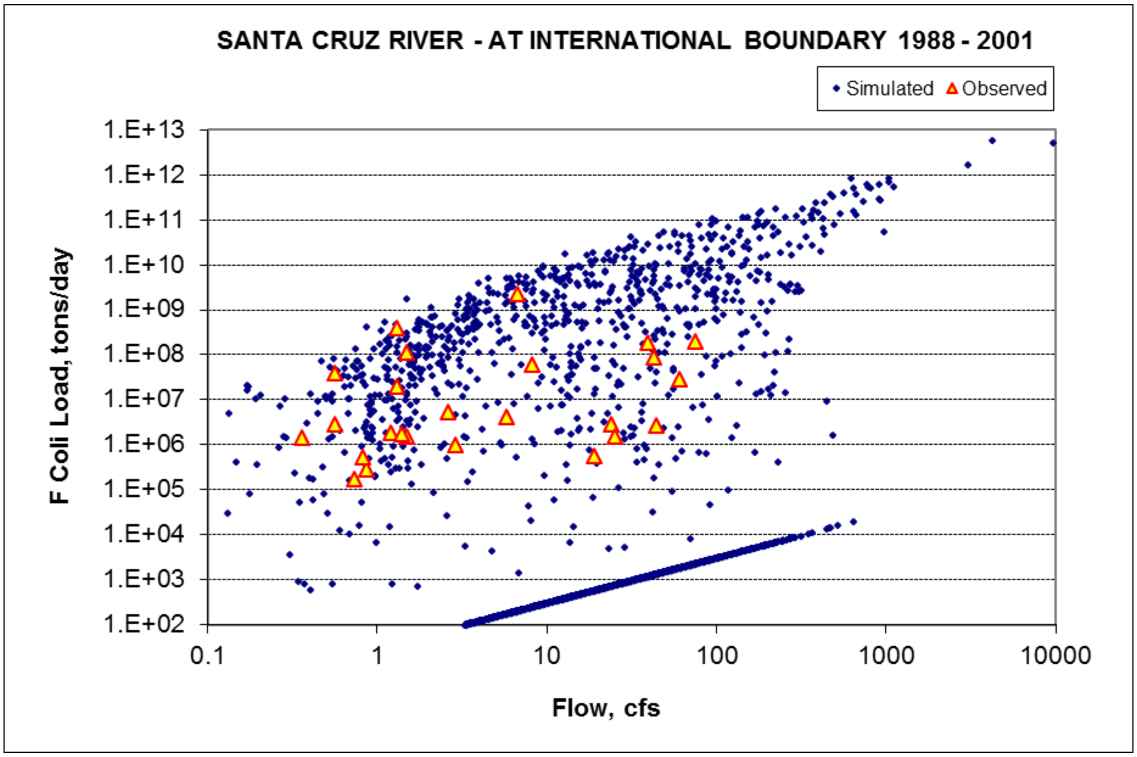

Figure A-40. Fecal Coliform Load Power Plot, Santa Cruz River at International Border (100239).

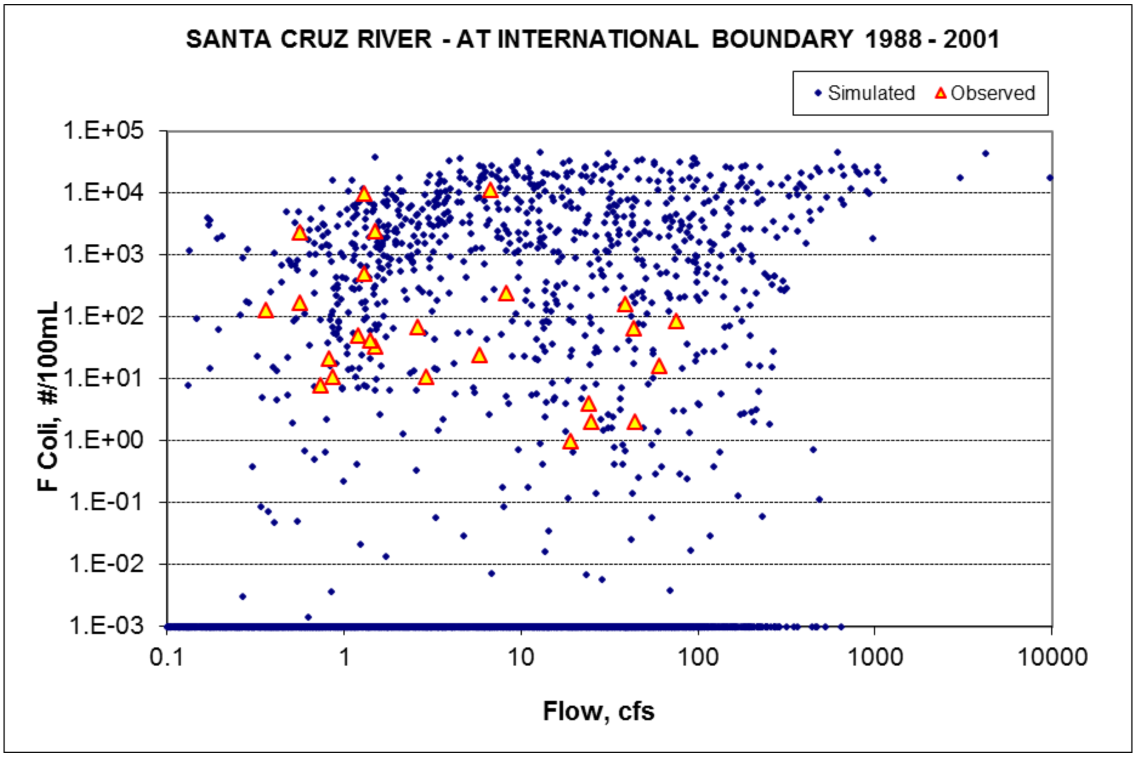

Figure A-41. Fecal Coliform Concentration Power Plot, Santa Cruz River at International Border (100239).

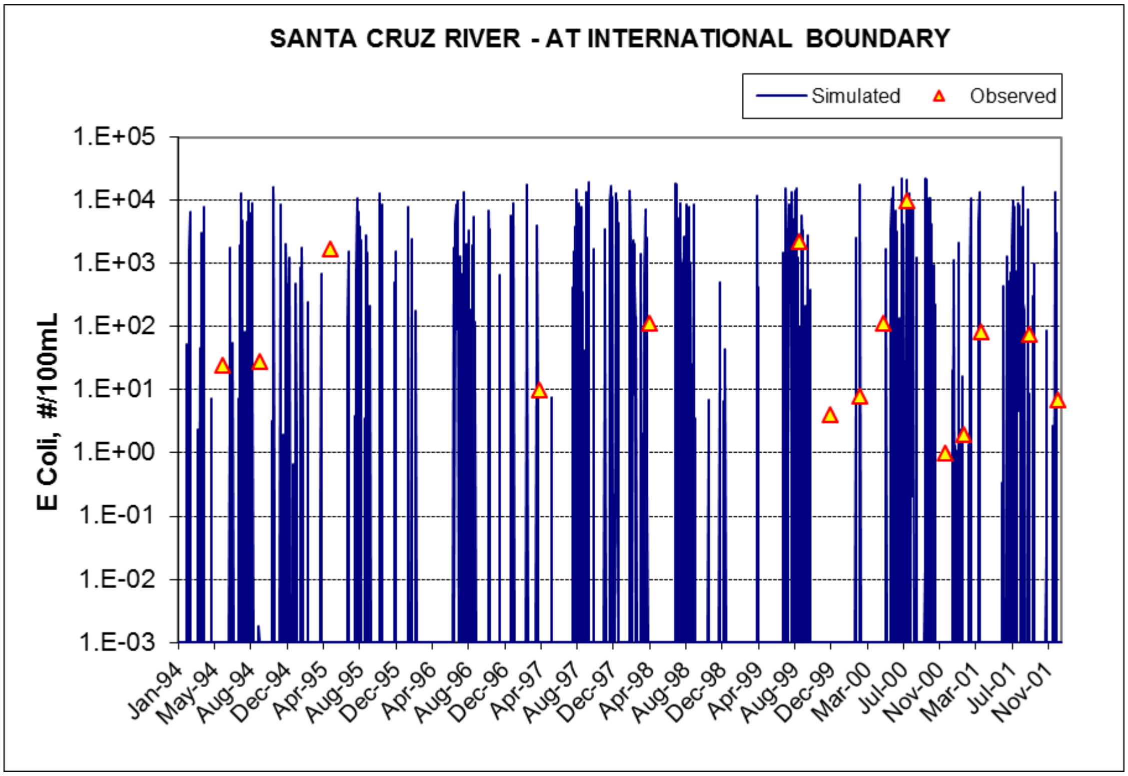

Figure A-42. *E. coli* Simulation, Santa Cruz River at International Border (100239), 1994-2001.

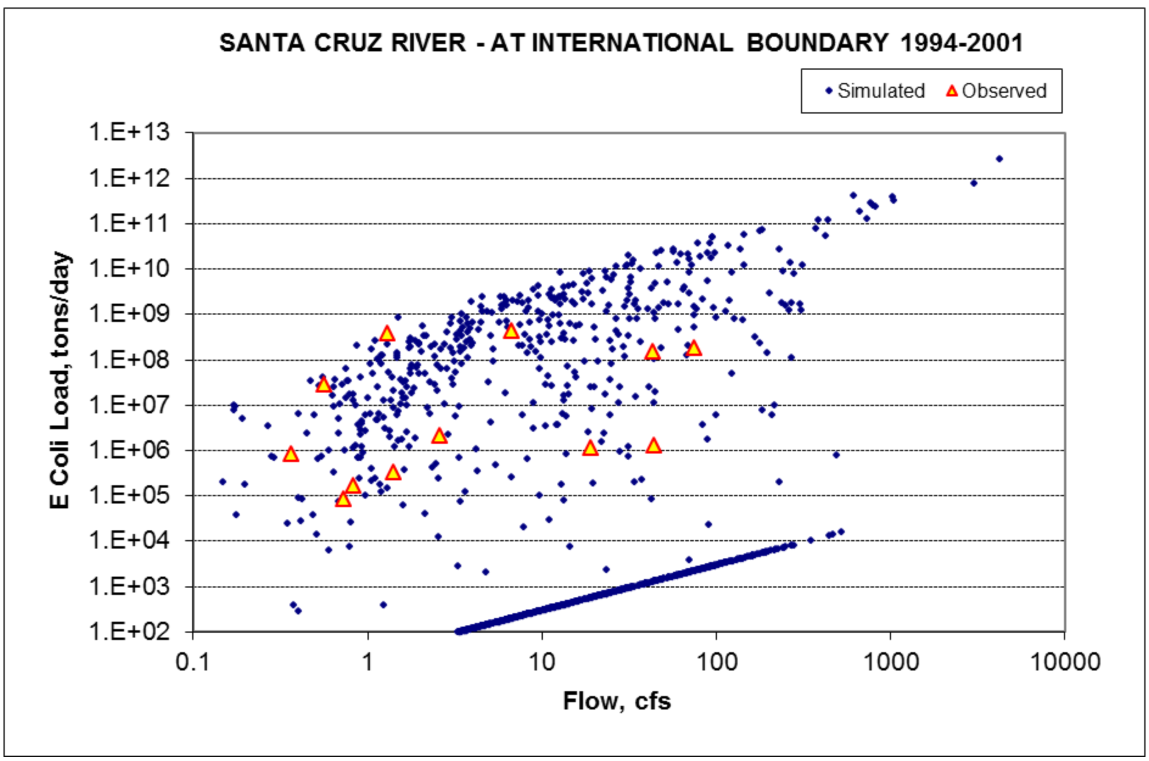

Figure A-43. *E. coli* Load Power Plot, Santa Cruz River at International Border (100239).

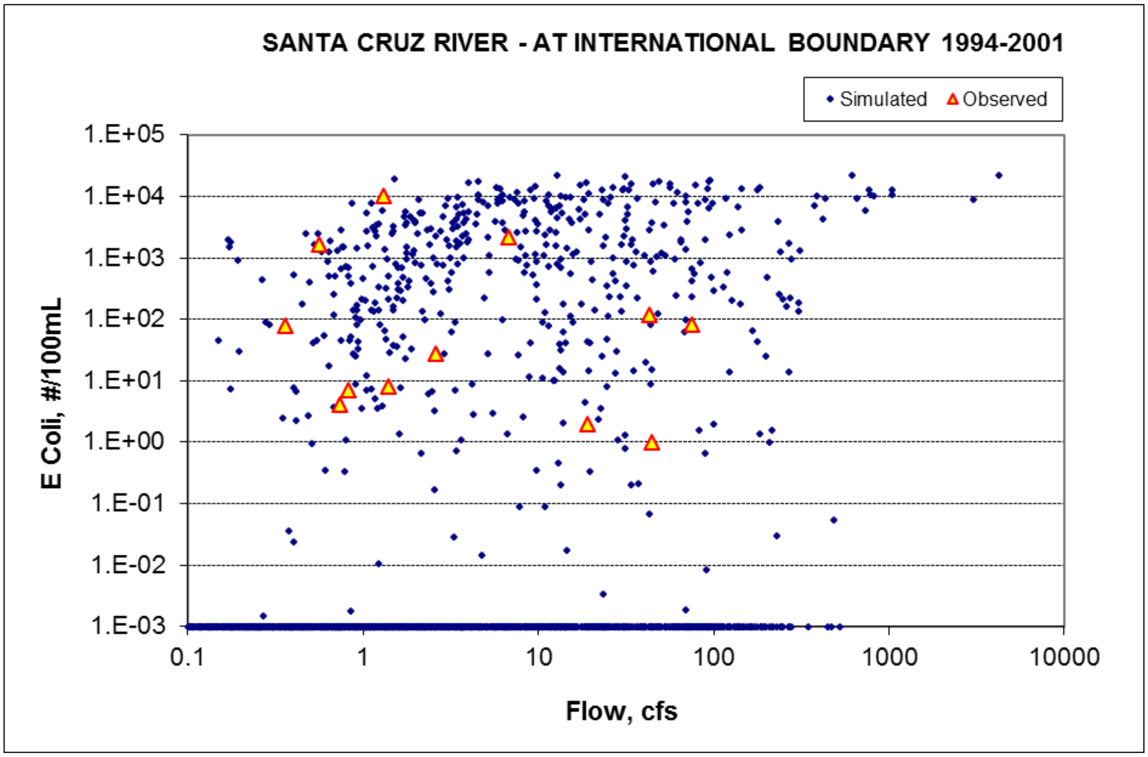

Figure A-44. *E. coli* Concentration Power Plot, Santa Cruz River at International Border (100239).

Stations were also analyzed on Potrero Creek (100571) and Nogales Wash (100251), all downstream of Nogales, Sonora, Mexico. There is no flow gaging available for the period of interest; therefore, a load comparison is not possible.

Comparison of observed and simulated concentrations in Potrero Creek at Ruby Road (Figure A-45 through Figure A-47) shows a reasonable agreement between observed and simulated peak concentrations, although the model often goes toward zero concentrations during dry weather, whereas dry weather observations are highly variable. In contrast, both fecal coliform and *E. coli* observations in Nogales Wash at Morley Street Tunnel (Figure A-48 through Figure A-51) show that bacterial concentrations crossing the border from Mexico are often under-estimated. This is confirmed by more recent observations of *E. coli* south of the Rt. 82 overpass (station 100701; Figure A-52).

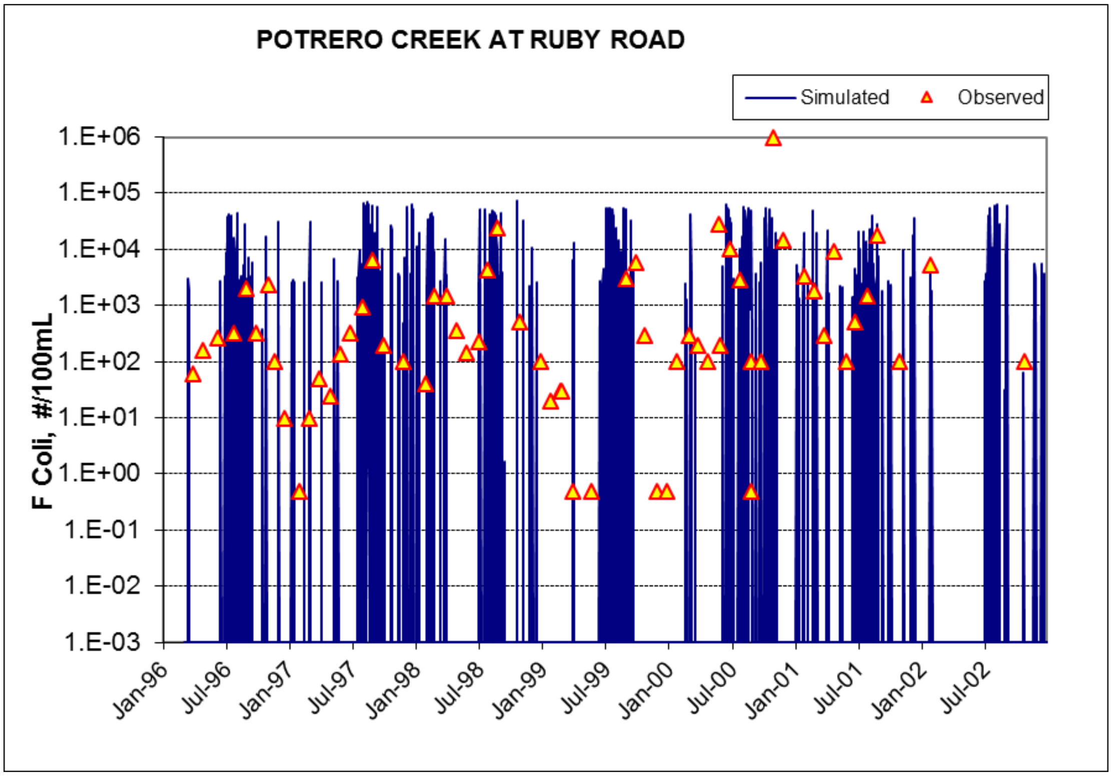

Figure A-45. Fecal Coliform Simulation, Potrero Creek at Ruby Road (100571), 1996-2002.

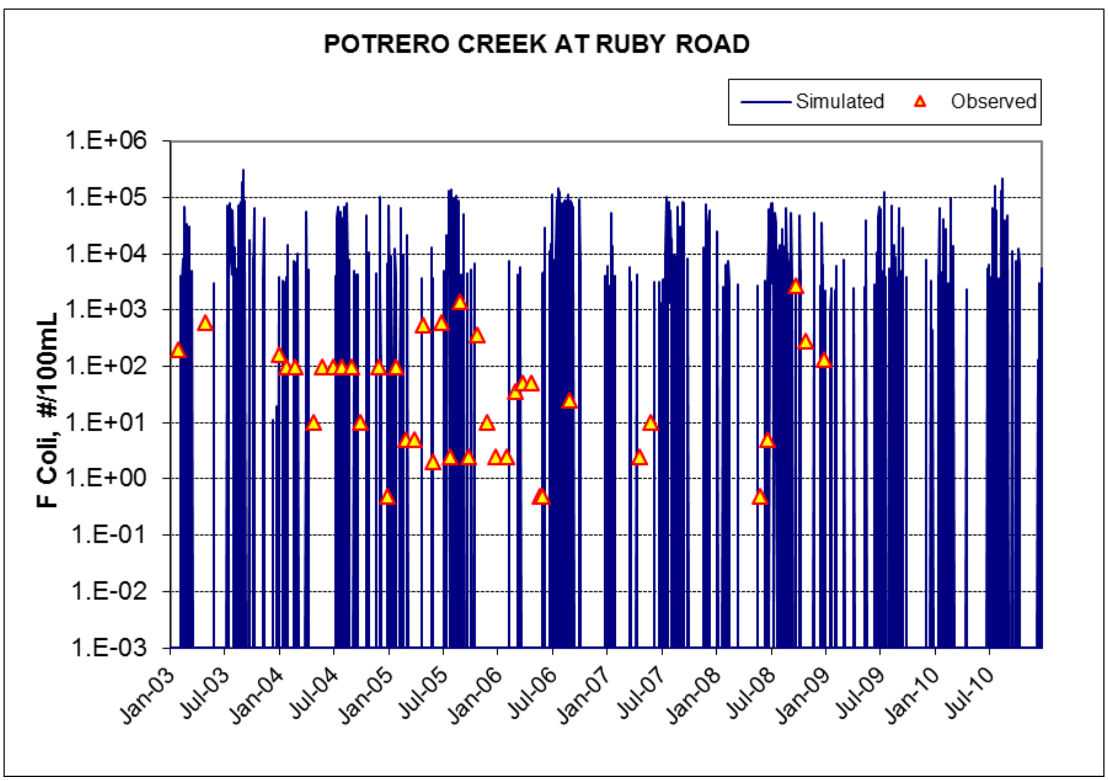

Figure A-46. Fecal Coliform Simulation, Potrero Creek at Ruby Road (100571), 2003-2010.

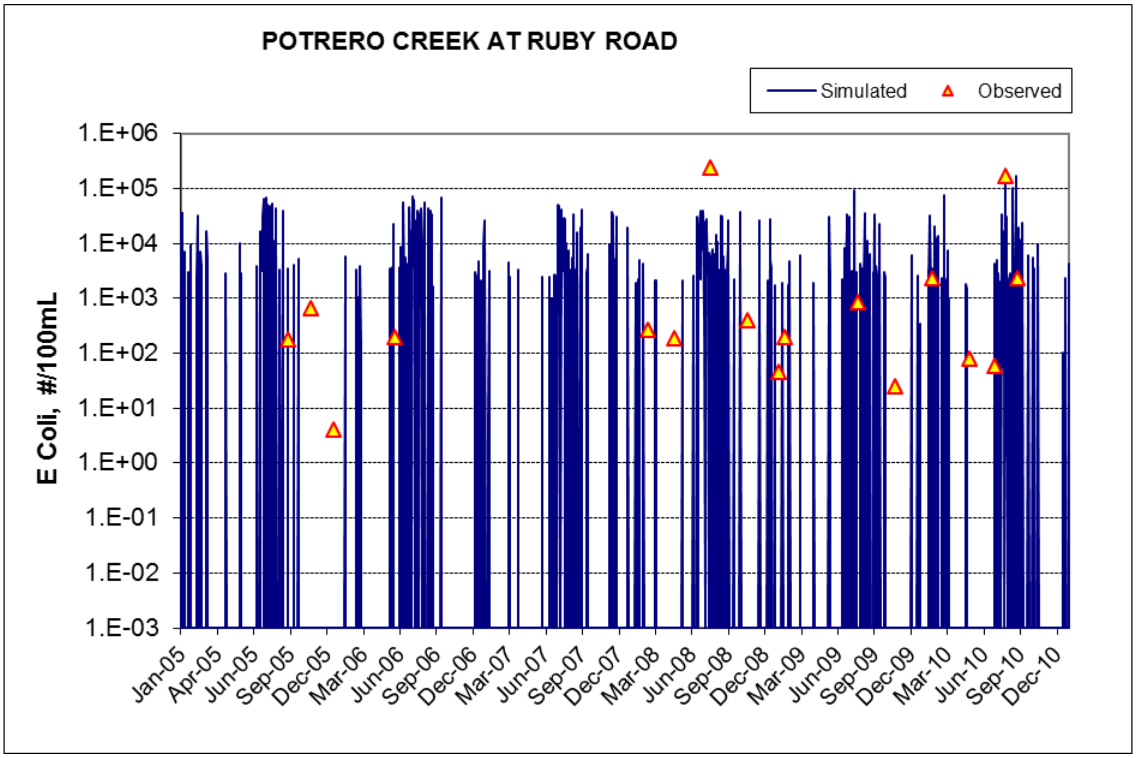

Figure A-47. ***E. coli*** **Simulation, Potrero Creek at Ruby Road (100571), 2005-2010.**

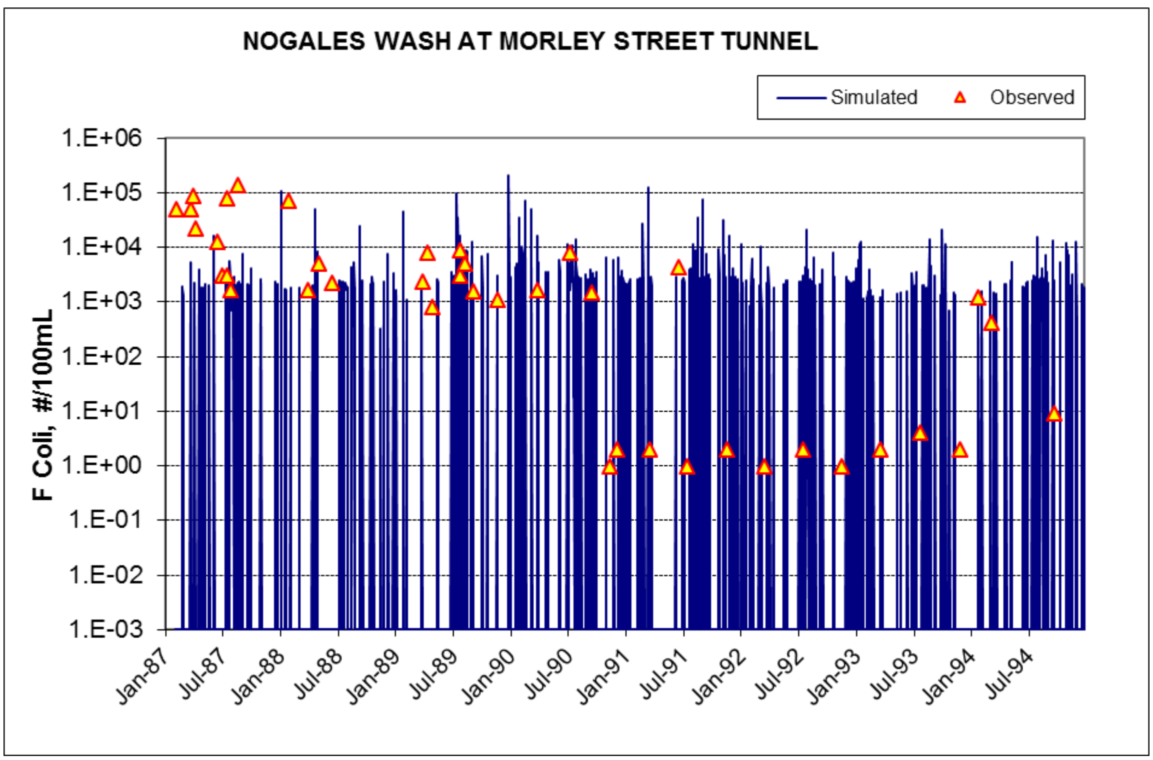

Figure A-48. Fecal Coliform Simulation, Nogales Wash at Morley St. Tunnel (100251), 1987-1995.

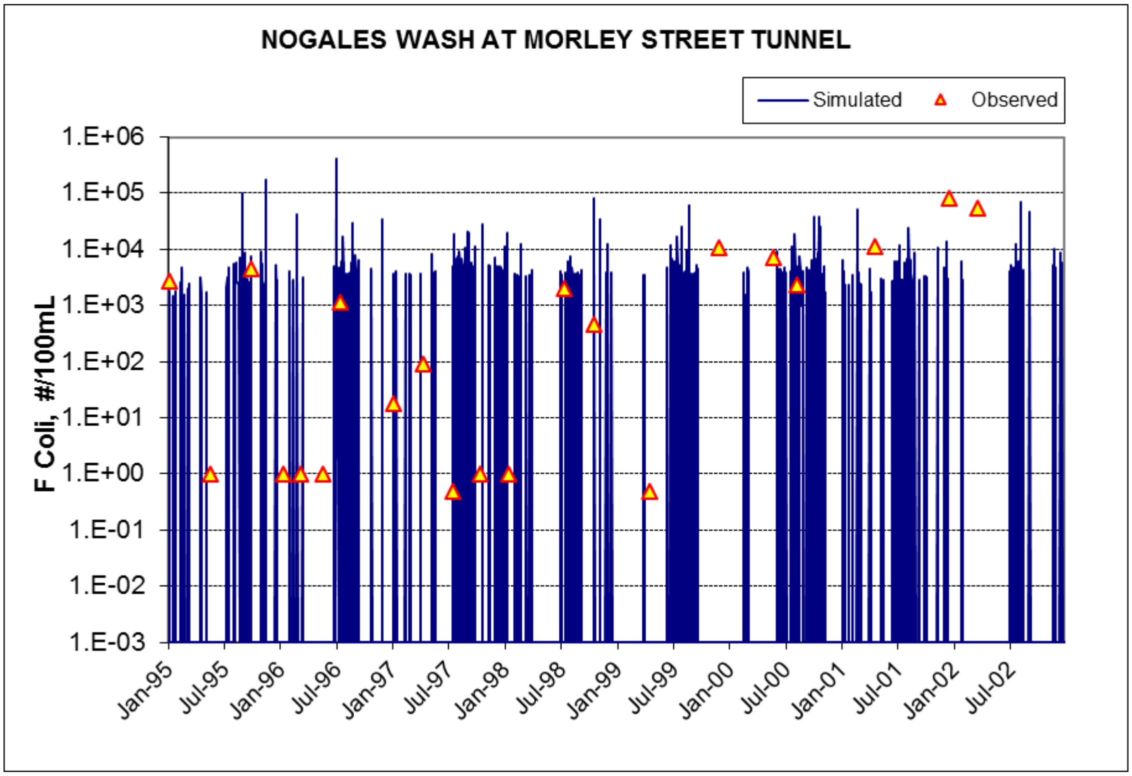

Figure A-49. Fecal Coliform Simulation, Nogales Wash at Morley St. Tunnel (100251), 1995-2002.

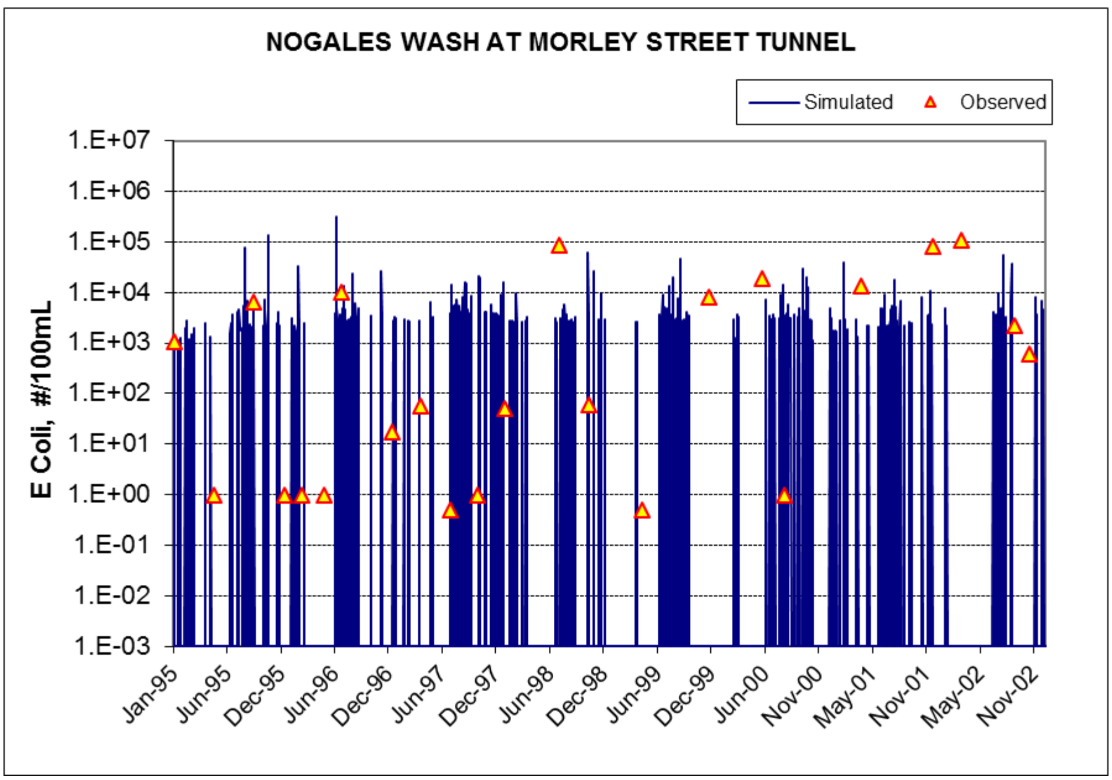

Figure A-50. *E. coli* Simulation, Nogales Wash at Morley St. Tunnel (100251), 1995-2002.

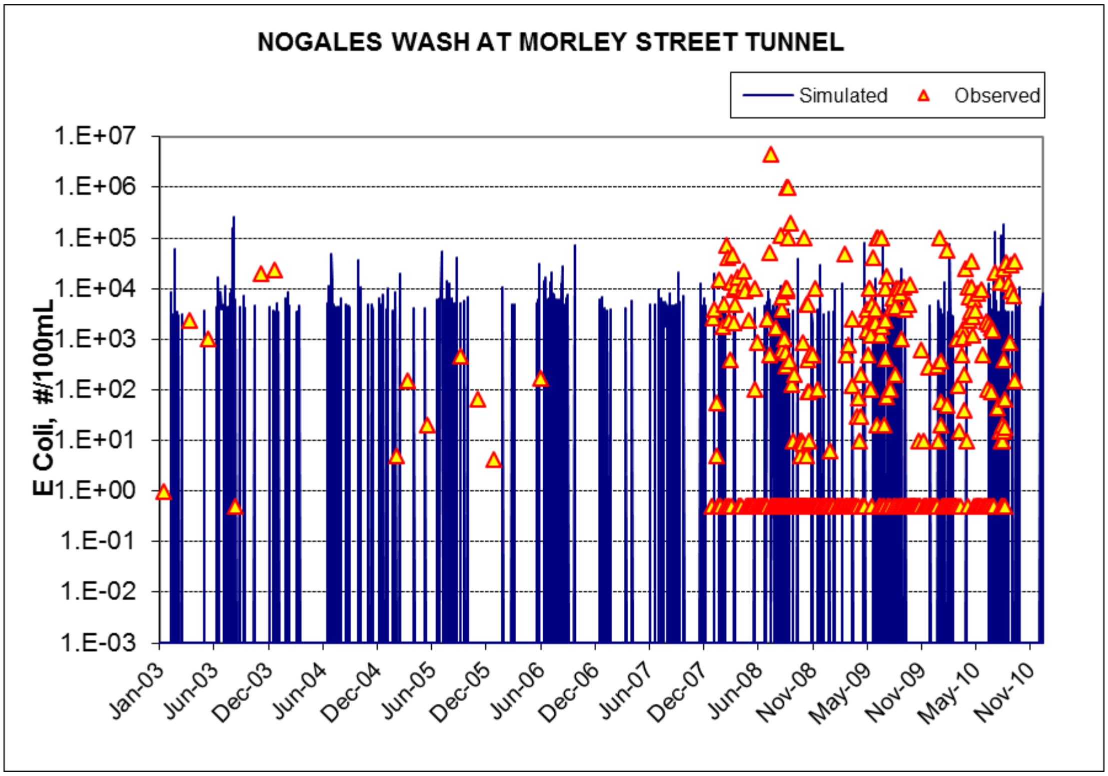

Figure A-51. ***E. coli*** **Simulation, Nogales Wash at Morley St. Tunnel (100251), 2003-2010.**

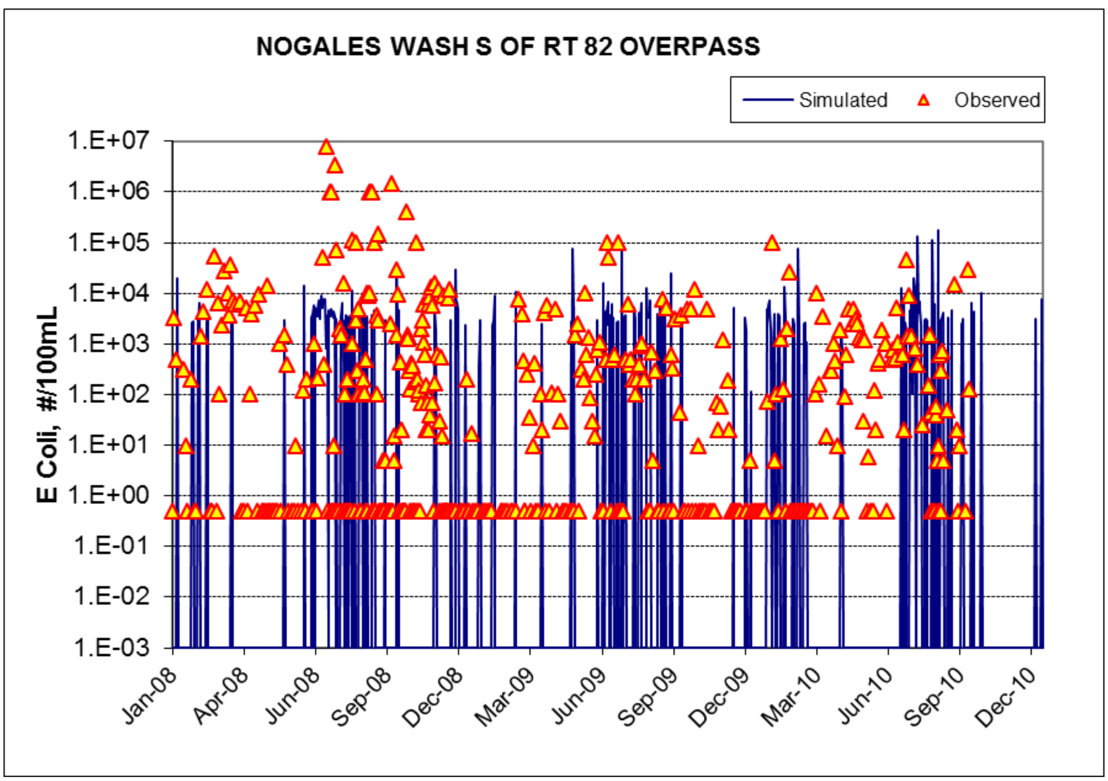

Figure A-52. ***E. coli*** **Simulation, Nogales Wash S. of Rt. 82 Overpass (100701), 2008-2010.**

5 Discussion

5.1 SWAT Model Bacteria Source Attribution

The model, subject to the many simplifying assumptions documented above, provides estimates of the fraction of bacterial load attributed to different nonpoint sources. For the USCR at the International Border (the sparsely inhabited drainage area from the headwaters in Arizona through the reach in Mexico upstream of Reach 1 or SWAT subbasin 119 in Figure A-1 and not including Nogales Wash), the simulated nonpoint fecal coliform load is split between cattle and wildlife (Figure A-53, note the logarithmic scale on the y-axis). The simulated *E. coli* load follows the same pattern as *E. coli* buildup rates and is proportional to fecal coliform rates.

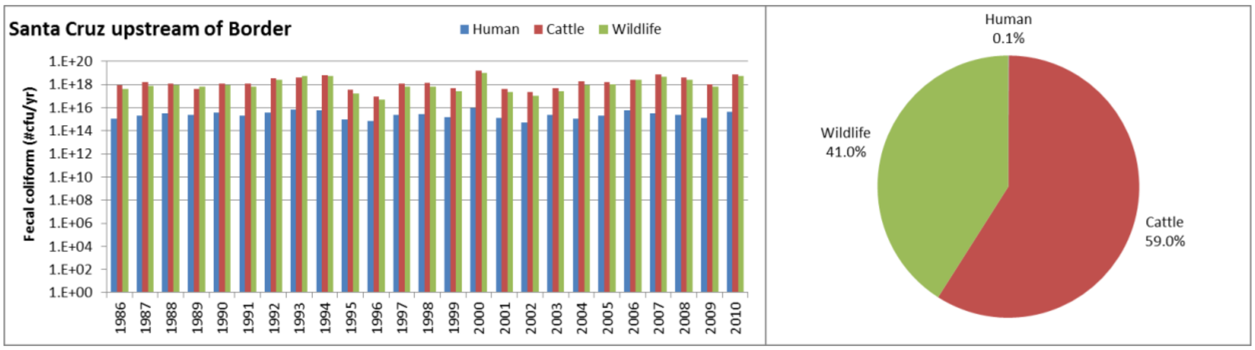

Figure A-53. Simulated Bacterial Load Sources for Santa Cruz River upstream of the International Border as absolute annual loads (bar chart) and overall relative contributions (pie chart).

Note: Percentage contributions rounded to the first decimal.

In contrast, the simulated load in Nogales Wash (Figure A-54) is predicted to be mostly from human sources – and is also likely under-estimated by the model. The under-estimation may represent a combination of loads from urban runoff and illicit discharges and is likely associated with the high proportion of impervious cover in the drainage area.

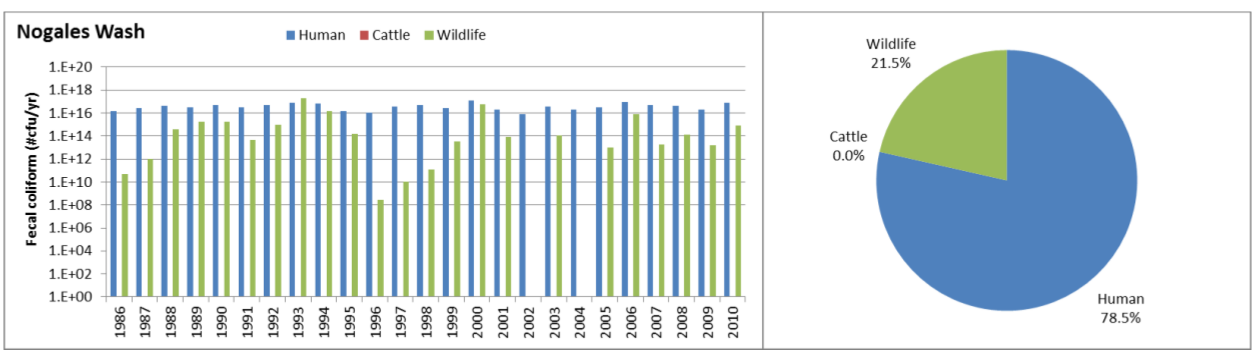

Figure A-54. Simulated Bacterial Load Sources for Nogales Wash Upstream of the International Border as absolute annual loads (bar chart) and overall relative contributions (pie chart).

Note: Percentage contributions rounded to the first decimal.

The USCR source bacterial load from the entire watershed area upstream of Tubac, inclusive of the four main stem reaches, Nogales Wash, and Potrero Creek, is estimated to be predominantly from cattle followed by wildlife sources, largely because of the high proportion of forest and rangeland compared to agricultural and urban land (Figure A-55). The modeled average annual loading within the project area (Reaches 1 through 5) estimate that loads from cattle are approximately 3 times the from wildlife, which are in turn 2 orders of magnitude greater than loads from human and urban sources.

Note that the figure shows loads from the land surface to the stream network and not the load that is present within the mainstem of the USCR. Because bacteria die off during transport, sources closer to impaired reaches are likely to be more consequential than sources at distance. Within the project area, most of the urban/human load occurs in the Nogales area, while cattle is the most important source overall. These predictions are based on the best available information, but may not fully represent the system.

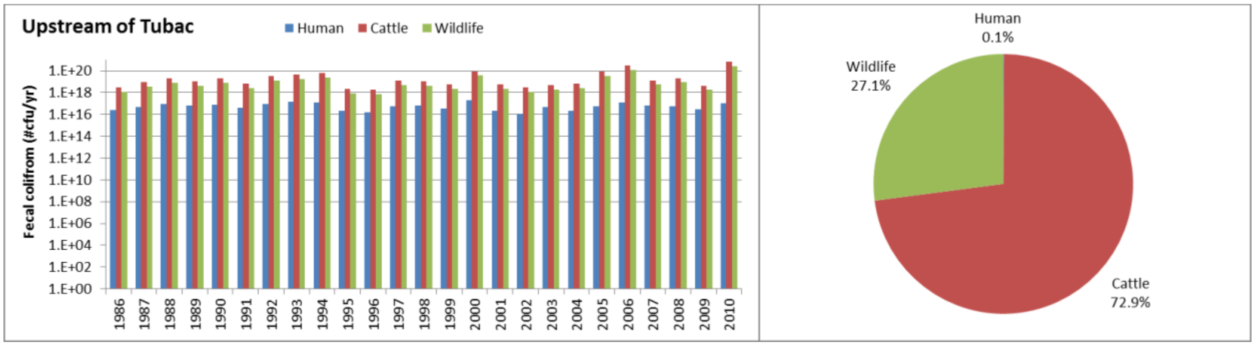

Figure A-55. Simulated Bacterial Load Sources from the International Border to Tubac, Including Nogales Wash and Potrero Creek as absolute annual loads (bar chart) and overall relative contributions (pie chart).
Note: Percentage contributions rounded to the first decimal.

5.2 Summary and Potential Enhancements to the Model

The SWAT model was used for this analysis because the hydrologic model had already been developed. SWAT, however, has a number of weaknesses for bacterial simulation – most notably omitting representation of bacterial loads from urban impervious surfaces. Further, analysis of the model shows that it has a weak ability to simulate flows at the daily scale, which makes comparison of model results to observed bacterial concentration data problematic.

The model suggests that there are significant un-simulated bacteria sources present on Nogales Wash, which may represent a combination of loads from urban runoff and illicit discharges or other dry weather sources. For the project area as a whole, wildlife sources are estimated to be the largest source of load. However, the model may be overestimating wildlife load relative to cattle loads because it does not fully account for cattle proximity to the river. Further evidence as to whether this is correct might be attainable from use of additional microbial source tracking markers for deer and other wildlife.

Watershed models of bacterial loading are often difficult to evaluate because bacterial concentrations can change rapidly and there is often low precision and reproducibility of analytical results. It is likely, however, that the model performance could be enhanced through a better simulation of hydrology – either by refining and recalibrating the SWAT model or by moving to a sub-daily watershed model such as Hydrologic Simulation Program – Fortran (HSPF) to better characterize the dynamic nature of the system. The bacterial simulation could also benefit from the addition of a component that can represent loading from urban impervious surfaces. Routines to handle this are available in HSPF and could be added to SWAT, although this would require code modification.

6 References

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Appendix B

SWAT Model Loading by Subbasin (Spreadsheet Tool)

October 2018

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Appendix B is a spreadsheet tool that provides a graphical summary of modeled loading for both fecal coliform and *E. coli* for each subbasin in the study area by modeled source category, represented by different land uses. The land uses in the model consist of URBN (urban), AGRL (agriculture), SWRN (barren), FRSD (deciduous forests), FRSE (evergreen forests), RNGE (grassland) and RNGB (shrubland).

The model was parameterized such that wildlife sources were limited to RNGE, RNGB, FRSD and FRSE land use categories; cattle to RNGE, RNGB, and AGRL, and human to URBN. Individual subbasin loading estimates may be retrieved from the tool. As noted in the full model calibration report, Appendix A to the CWP, the model is subject to uncertainties in simulating nonpoint loading and results are best used to evaluate hypotheses regarding the spatial distribution of bacterial loads and the potential significance of different source types.

The tool consists of three parts:

1. A clickable subbasin map that shows the average annual bacteria loads being produced by each subbasin in the study area using a color map.
2. Clicking a subbasin in the map updates the chart on the top right that shows the average annual (left y-axis), and mean, median, min and max unit area loads (right y-axis) from each source category for the selected subbasin. These charts can be exported to Microsoft Word® by clicking the button on the upper right corner of the tool.
3. A stacked column chart shows the total or % bacteria load by source category for all the subbasins.

The SantaCruzLoadingTool.xlsm file and the ImplementationPlanningTool.xlsm file can be downloaded at the following location: http://www.azdeq.gov/node/677

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Appendix C

Supplemental TMDL Development Information for the Upper Santa Cruz River Watershed

October 2018

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The TMDL represents the maximum loading that can be assimilated by a waterbody while still achieving applicable water quality standards. The currently impaired designated uses for the USCR subwatershed include PBC and FBC recreation. The applicable WQS are described in Section 5.1.1 of the CWP. Targets designed to achieve these criteria are identified for the USCR subwatershed TMDL in Section 5.3.1 of the CWP. TMDL development also involves a linkage analysis that connects TMDL targets with potential sources (see Section 5.3.2 of the CWP). The loading capacity (or maximum allowable load) was then defined and each source category was provided with an allocation. The TMDL includes concentration-based allocations for all potential sources. This appendix provides additional information needed to satisfy USEPA TMDL review requirements, consistent with the EPA's regulations which define *"load"* as *"an amount of matter that is introduced into a receiving water"* (40 CFR §130.2). Specifically, loading-based TMDL calculations are provided and allocations are presented for the consistent sources of bacteria loading to the impaired segments.

Establishment of the TMDL

A waterbody's loading capacity represents the maximum rate of loading of a pollutant that can be assimilated without violating WQC (40 CFR 130.2(f)). Establishing the relationship between instream water quality and source loading is an important component of TMDL development. It allows the determination of the relative contribution of sources to total pollutant loading and the evaluation of potential changes to water quality resulting from implementation of various management options. This relationship can be developed using a variety of techniques ranging from qualitative assumptions based on scientific principles to numerical computer modeling. The load-based TMDLs for the USCR subwatershed were developed using the load duration curve (LDC) method to assure compliance with the stream TMDL numeric targets (which are equivalent to the WQC) at varying flow conditions.

The load duration analysis utilizes flow duration intervals, as discussed in Section 5.3.2.1 of the CWP, to identify flow regimes for 2001-2010. The loading capacity can be calculated by multiplying instream flow values by the numeric target concentration and a conversion factor (Table C-7). This step forms a trendline based on flow conditions, which represents the assimilative capacity of the stream at varying flow conditions. Both the geometric mean and single sample maximum TMDL numeric targets were used to calculate loading capacity curves for each reach. These loading capacities, or assimilative capacities, were calculated for each segment and are illustrated by trendlines in the load duration curve graphs (Figure C-56 to Figure C-61); the red line represents the single sample maximum loading capacity and the blue line represents the geometric mean loading capacity.

In addition, loads were calculated for points of observed data (Table C-7). These loads were compared to the single sample maximum loading capacity curve. Points that plot above this line represent an exceedance of the standard/assimilative capacity while loads below are in compliance. The LDC plots (Figure C-62 to Figure C-67) reflect the 2001-2010 data presented in the water quality duration curves; therefore, the discussion in Section 5.3.2.2 of the CWP about flow regimes and associated inferences about sources of *E. coli* to each segment are relevant to the load duration curves as well.

Table C-7. Calculation of bacteria loads.

Load *(organisms/day)* = Concentration *(org/100mL)* * Flow *(cfs)* * Factor			
multiply by **3785.2** *to convert*	mL per gallon	⇨	organisms / 100 gallon
divide by **100** *to convert*		⇨	organisms / gallon
multiply by **7.48** *to convert*	gallon per ft^3	⇨	organisms / ft^3
multiply by **86,400** *to convert*	seconds per day	⇨	ft^3 / day
divide by **1,000,000,000**	billion	⇨	billion-organisms
multiply by **0.02446** *to convert*	**(organisms/100mL) * ft^3 / sec**	⇨	**billion-organisms / day**

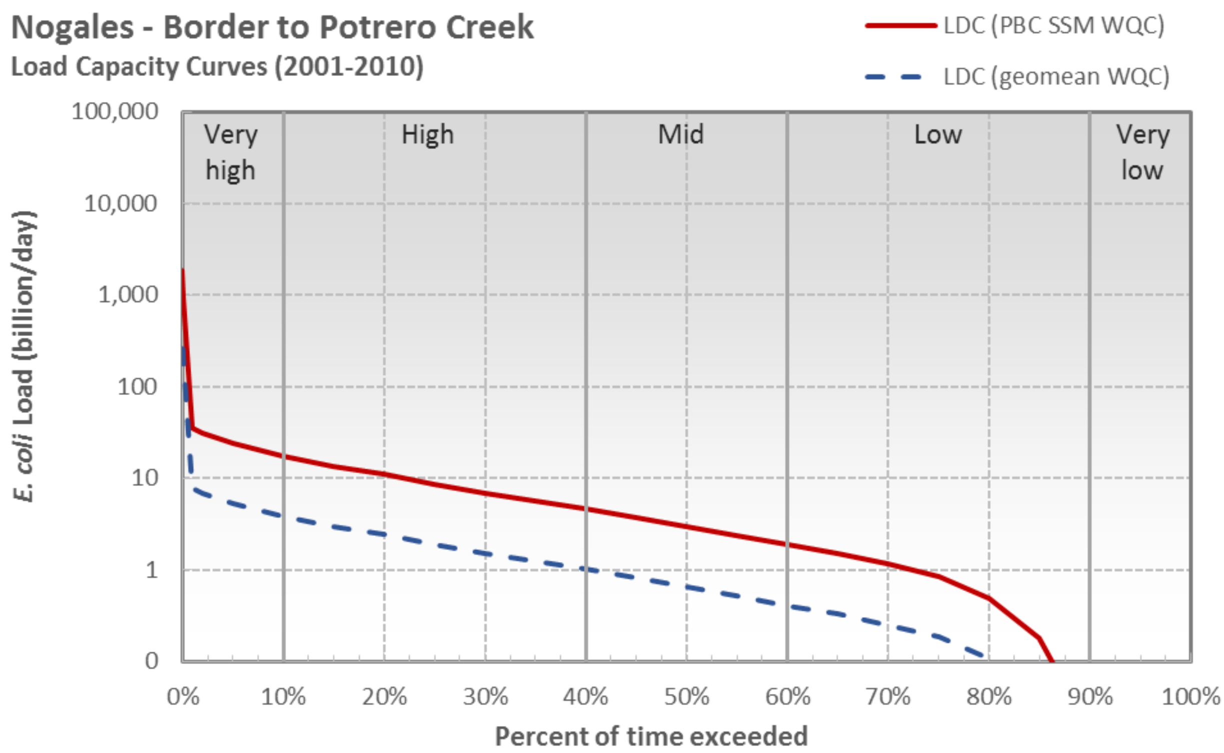

Figure C-56. Load Capacity Curves for Nogales – Border to Potrero Creek.

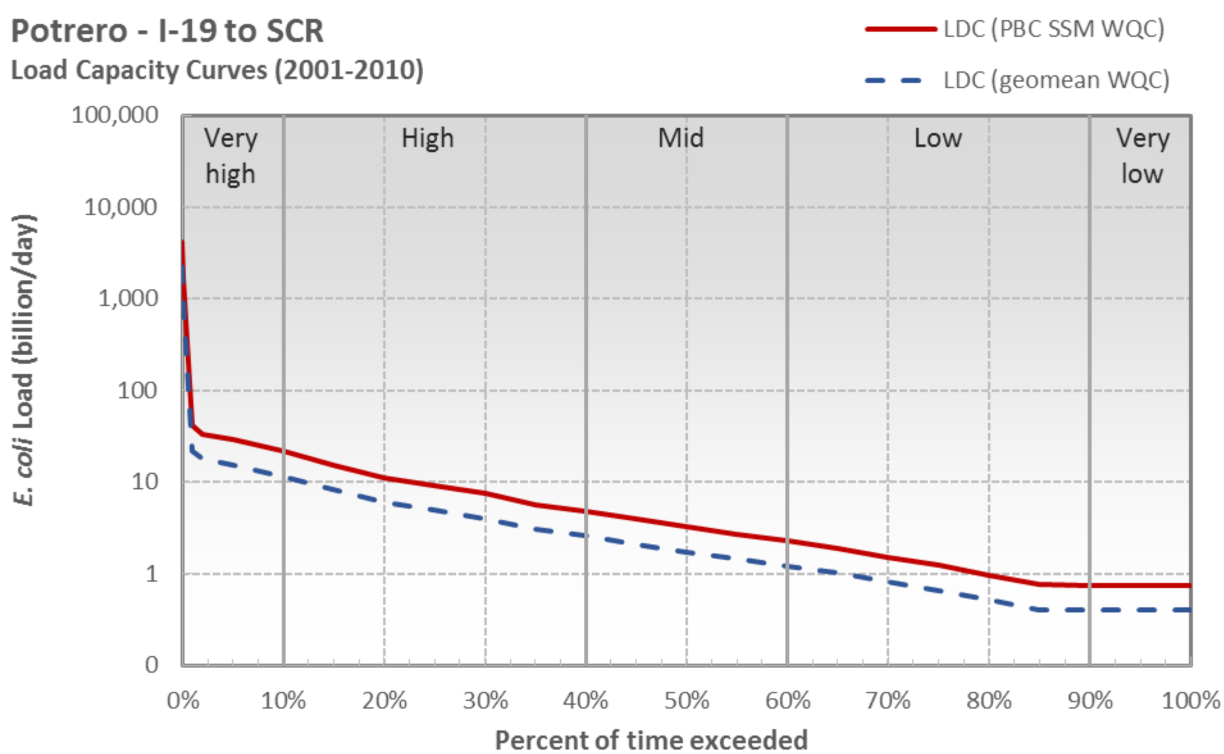

Figure C-57. Load Capacity Curves for Potrero – I-19 to SCR.

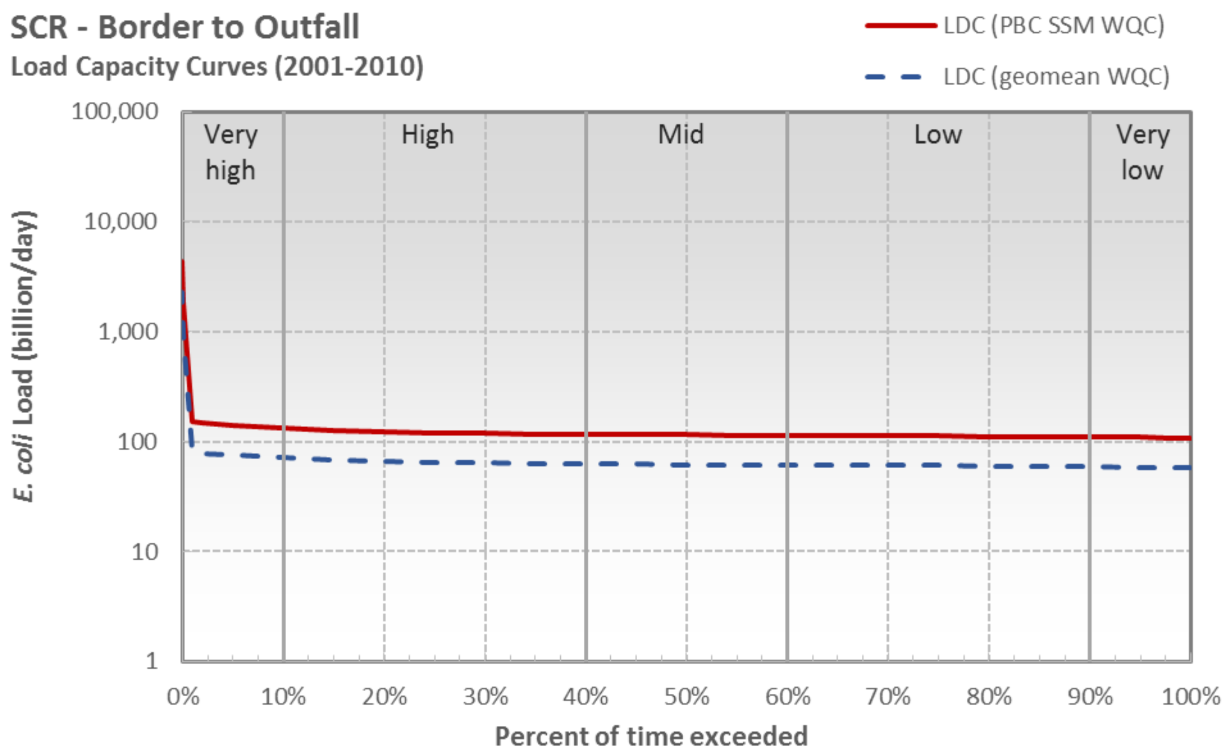

Figure C-58. Load Capacity Curves for SCR – Border to Outfall.

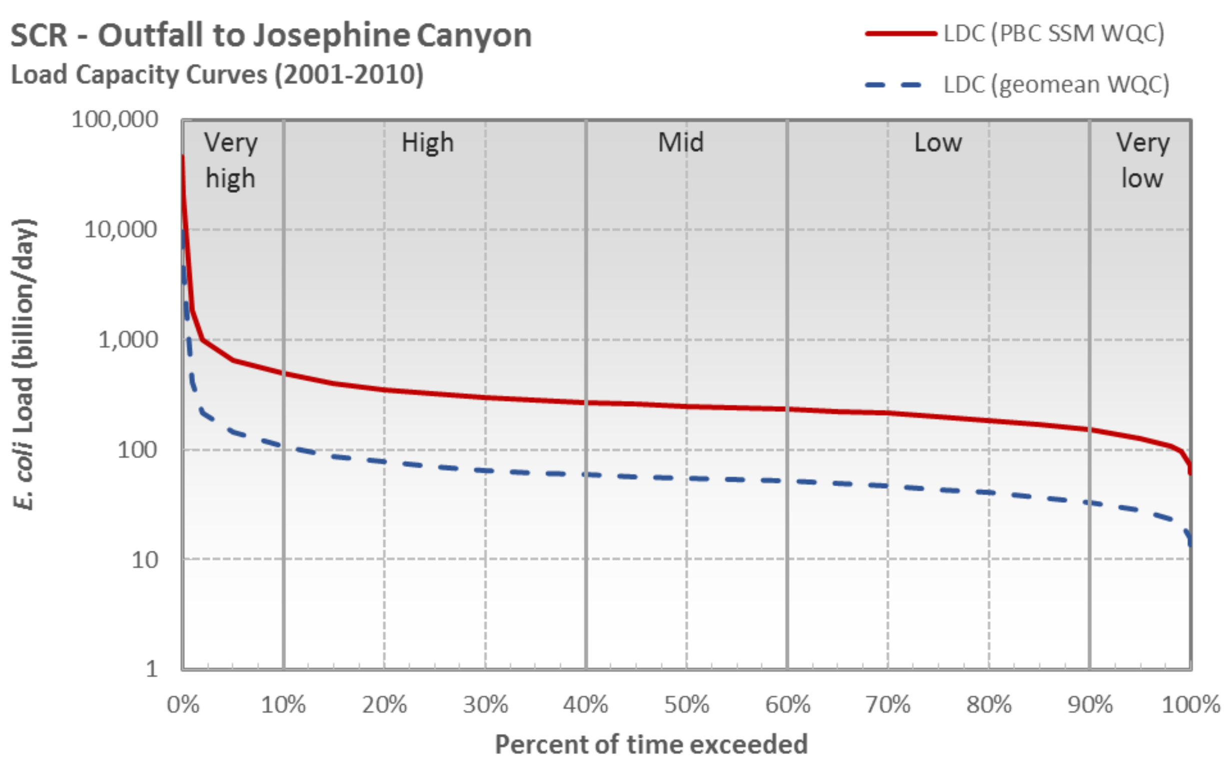

Figure C-59. Load Capacity Curves for SCR – Outfall to Josephine Canyon.

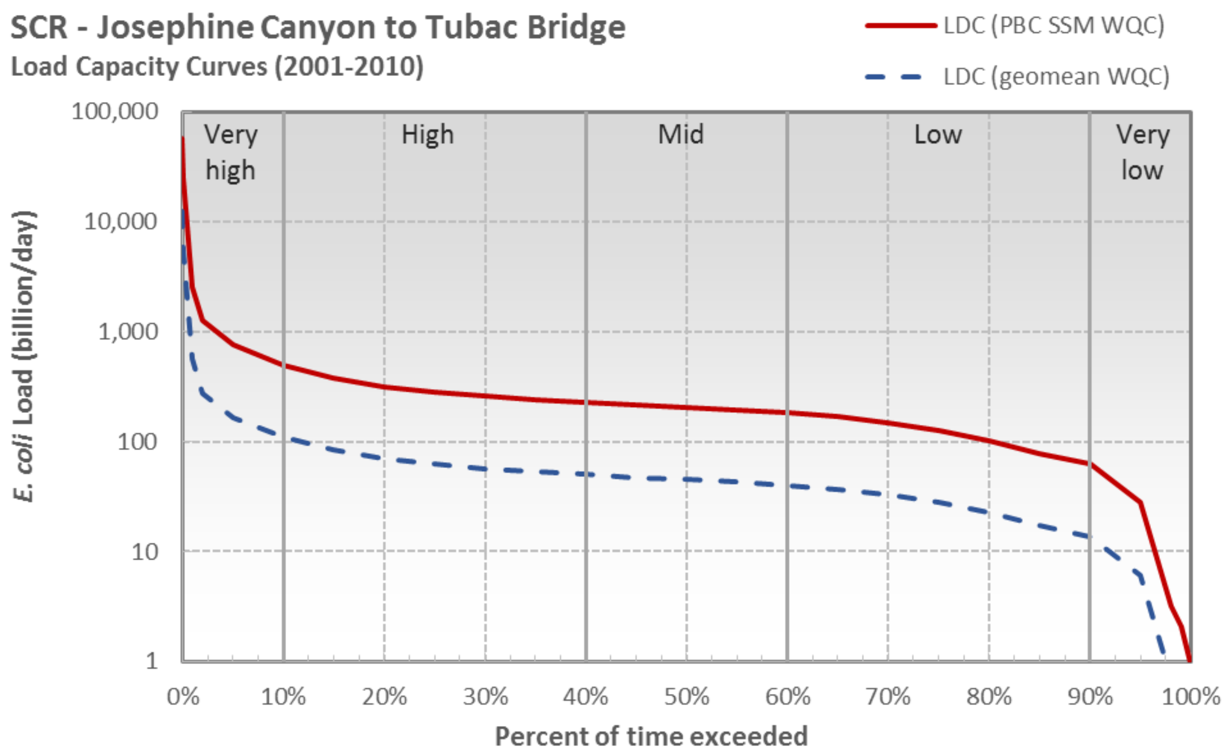

Figure C-60. Load Capacity Curves for SCR – Josephine Canyon to Tubac Bridge.

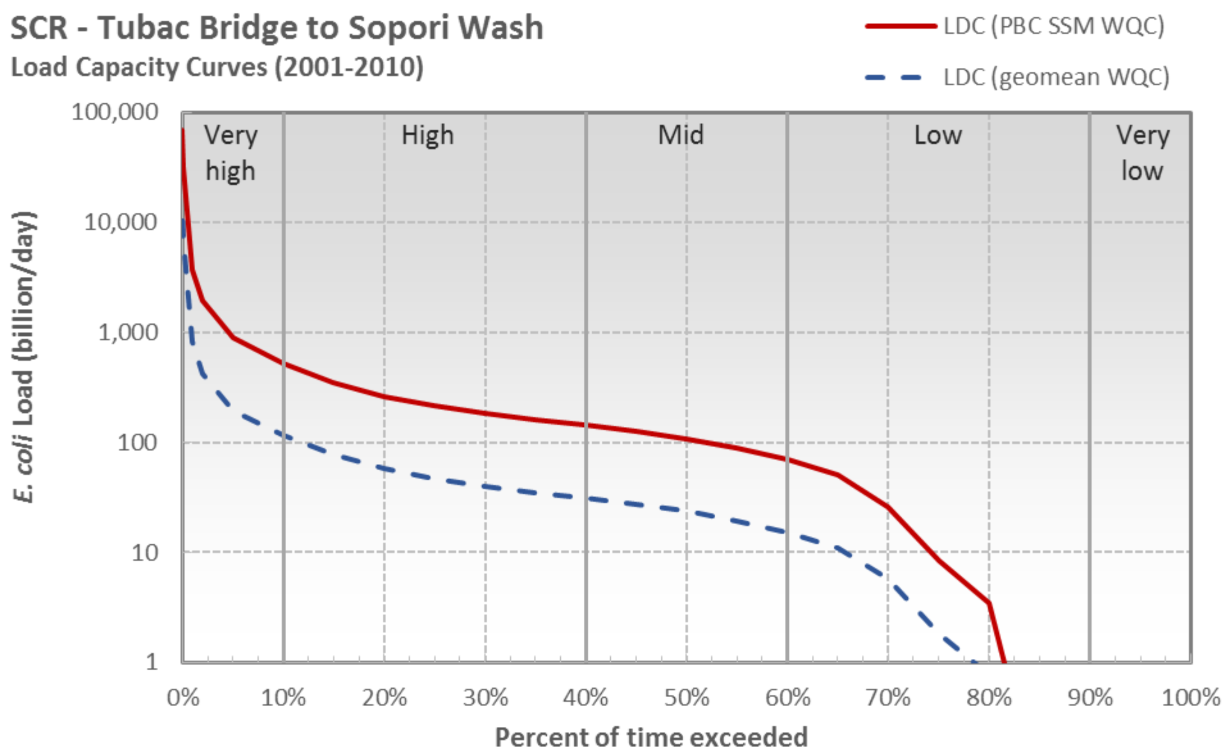

Figure C-61. Load Capacity Curves for SCR – Tubac Bridge to Sopori Wash.

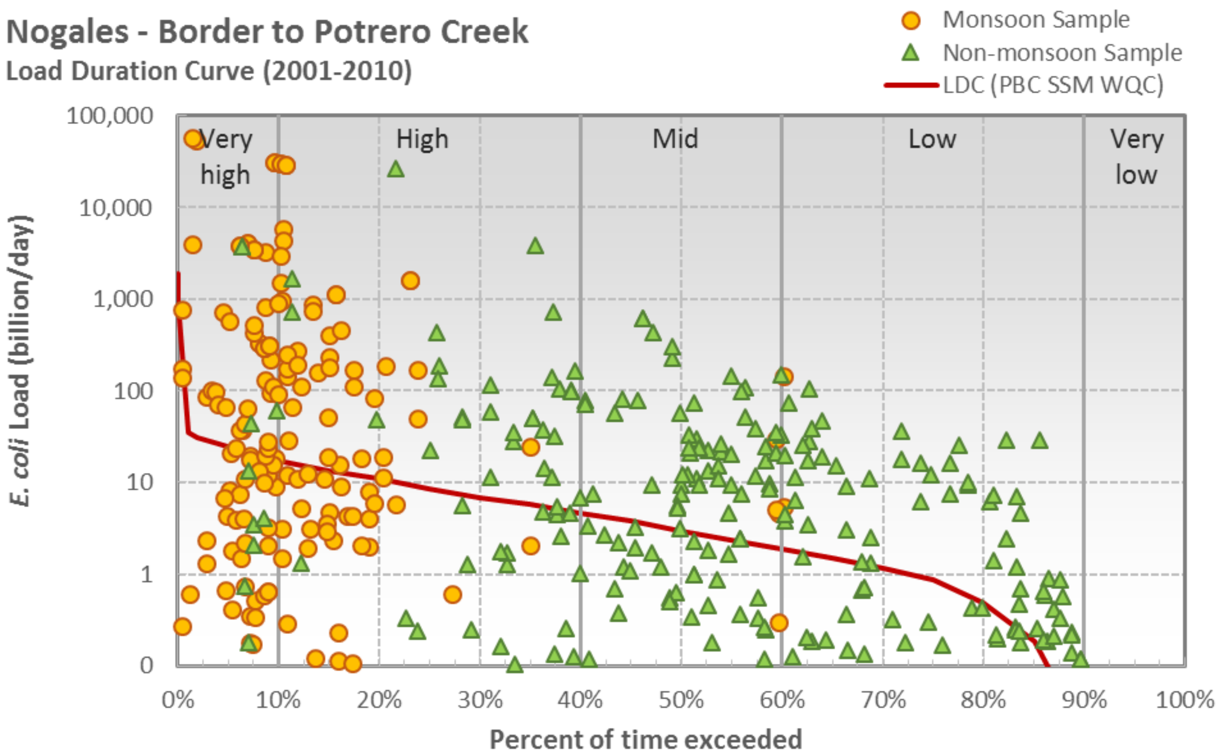

Figure C-62. Load Duration Curve and Observed Loads for Nogales – Border to Potrero Creek.

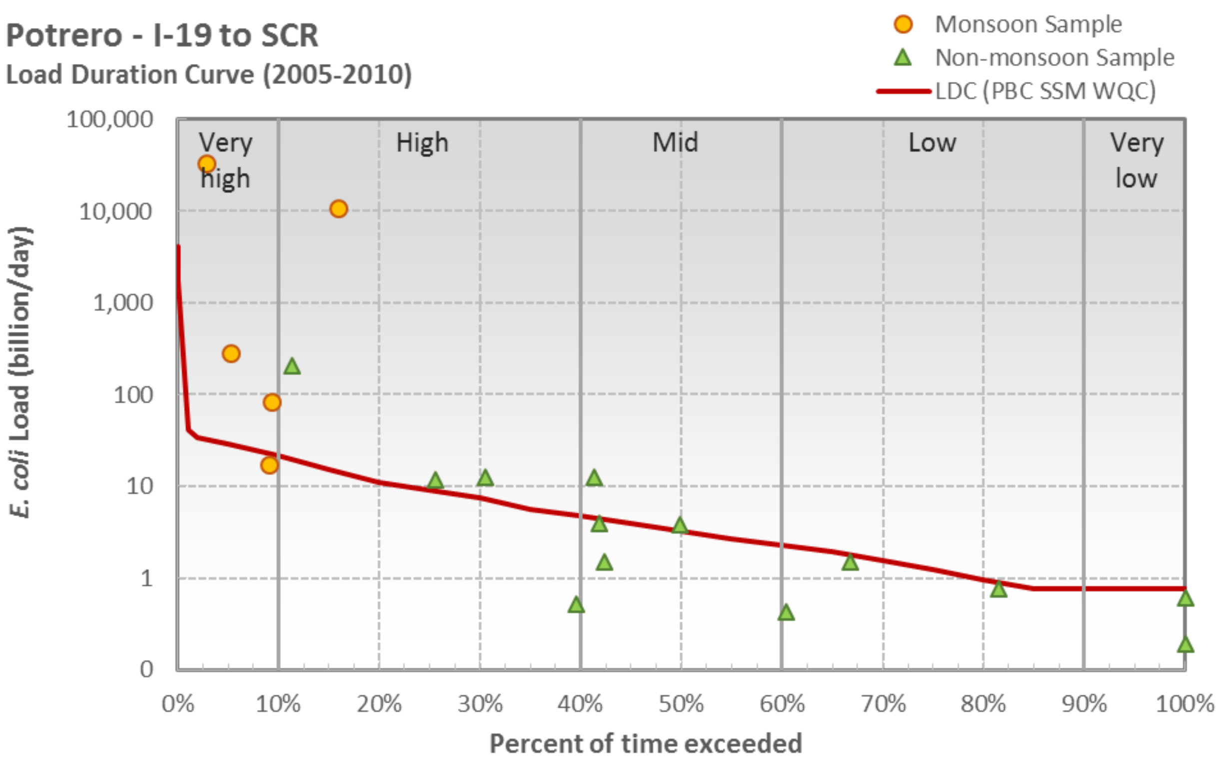

Figure C-63. Load Duration Curve and Observed Loads for Potrero – I-19 to SCR.

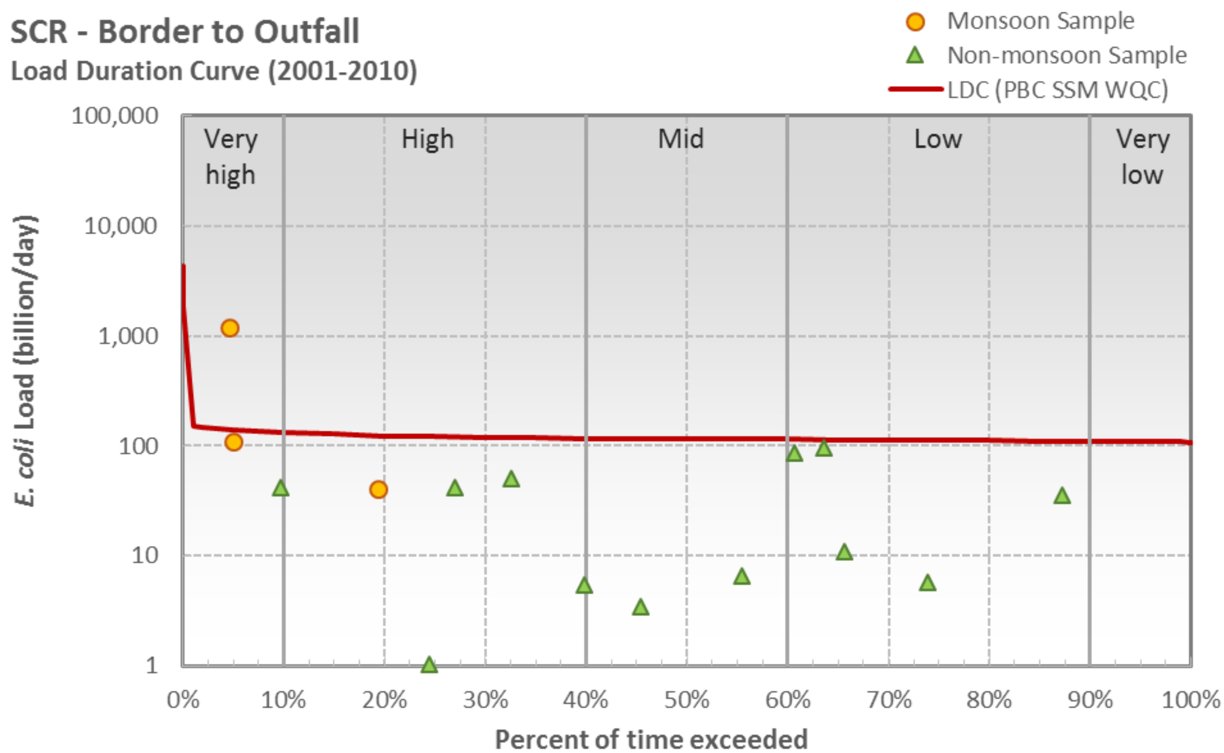

Figure C-64. Load Duration Curve and Observed Loads for SCR – Border to Outfall.

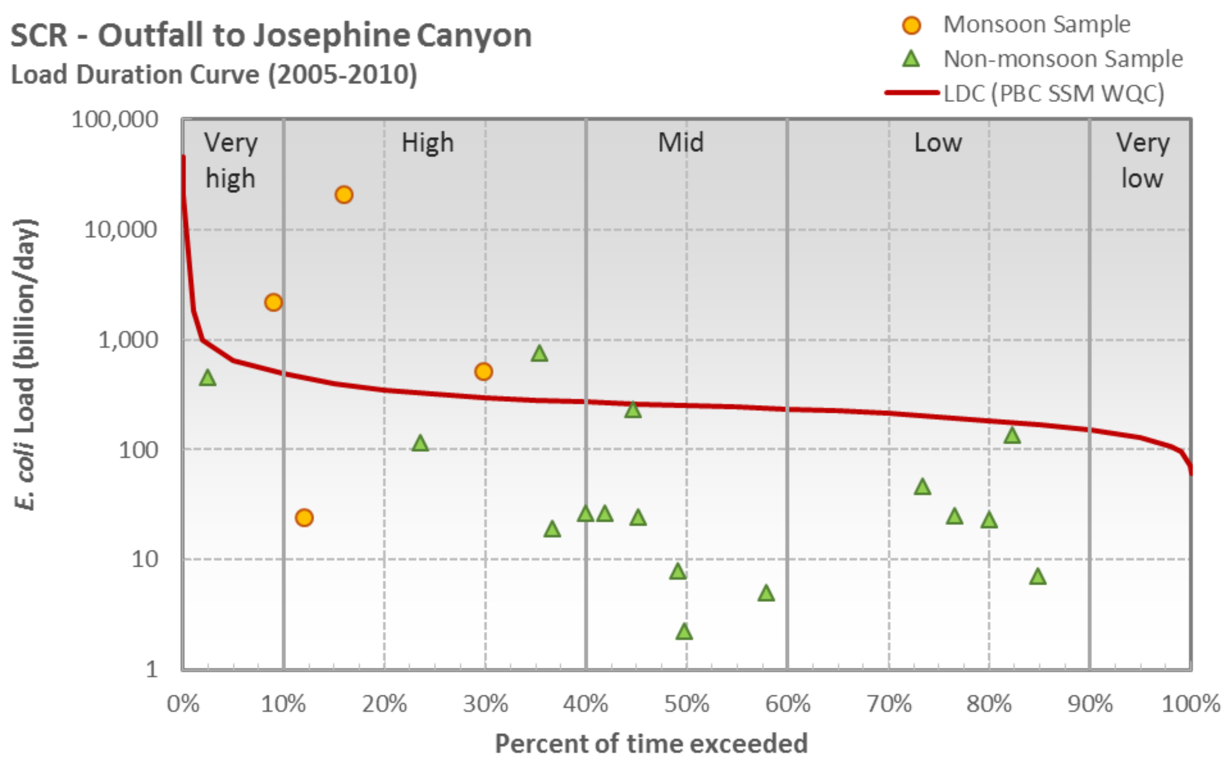

Figure C-65. Load Duration Curve and Observed Loads for SCR – Outfall to Josephine Canyon.

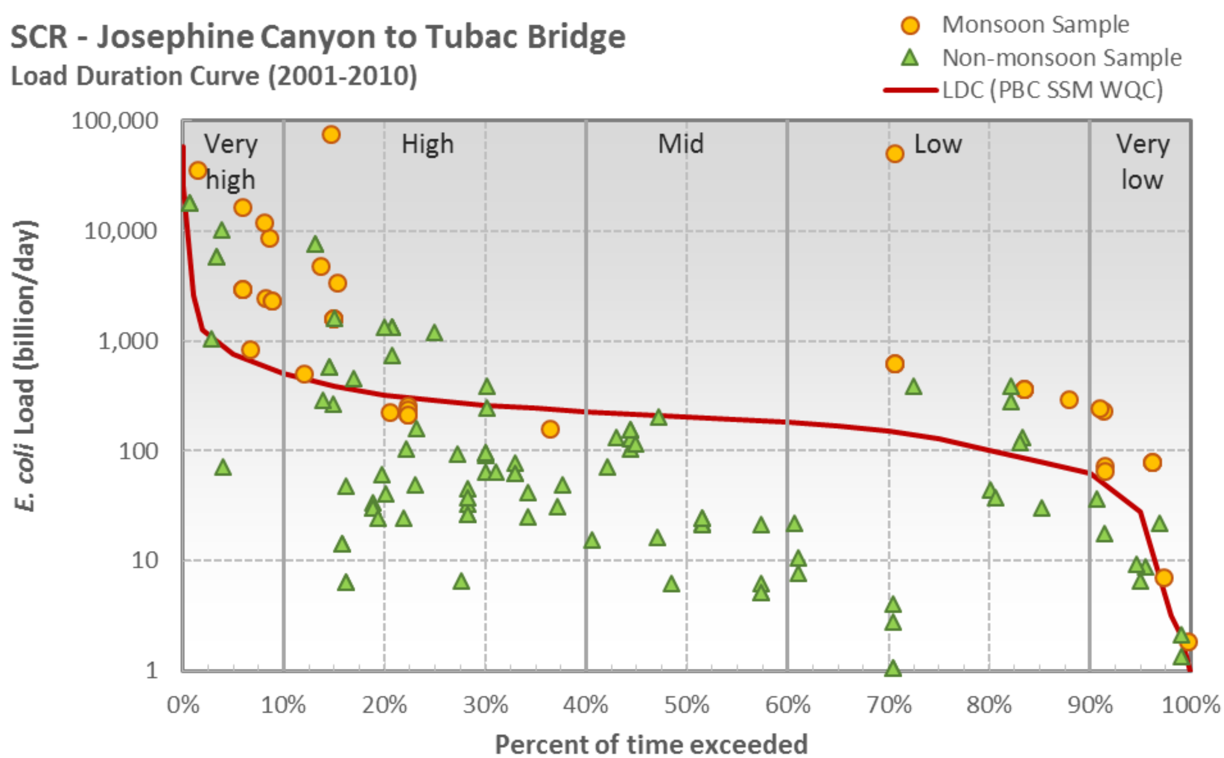

Figure C-66. Load Duration Curve and Observed Loads for SCR – Josephine Canyon to Tubac Bridge.

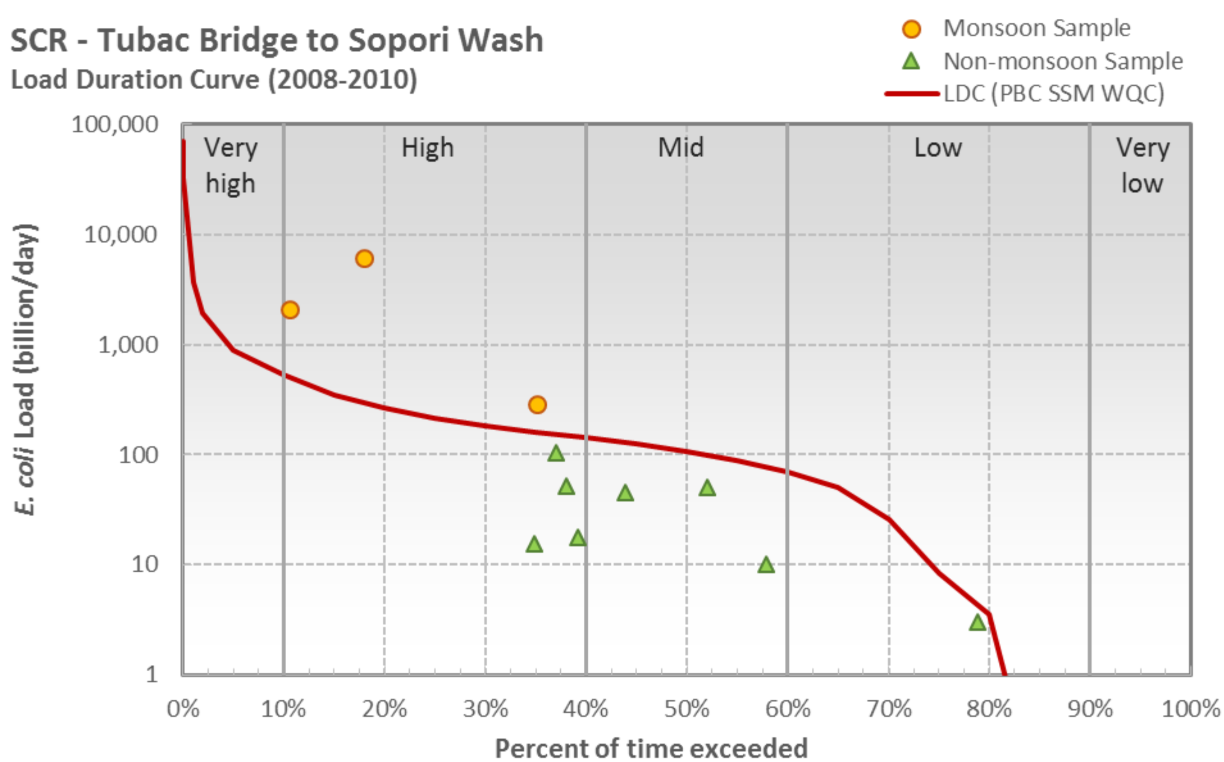

Figure C-67. Load Duration Curve and Observed Loads for SCR – Tubac Bridge to Sopori Wash.

Loading Capacity

Load duration curves were developed for each impaired reach to quantify reach-specific loadings. Loading capacities were then calculated using the equation in Table C-7 for the two different TMDL numeric targets that represent different averaging periods (Table C-8):

- Daily maximum TMDL: calculated using the single sample maximum TMDL numeric target and the average flow from a representative wet year (determined to be 2006 based on an assessment of the 2001-2010 SWAT modeled flows).
- Long-term average TMDL: calculated using the geometric mean TMDL numeric target and the average flow from the 2001-2010 SWAT model output.

These loading capacities were then allocated to the consistent bacteria sources to each impaired reach for both averaging periods. Details associated with the load-based allocation calculations are presented below. These loads are cumulative in nature with SCR – Tubac Bridge to Sopori Wash representing the full suite of loading conditions in the project area; however, during typical conditions the river loses flow as it progresses downstream of the WWTP outfall.

Existing loads were also calculated using the equation in Table C-7 based on observed concentrations for data from 2001-2010 (this time period was selected because it overlaps with the available SWAT model flows needed to assign flow regimes) (Table C-9). Existing loads were based on the 90th percentile concentration of all 2001-2010 data as well as the 90th percentile of post-upgrade *E. coli* concentrations for the same time period. The difference between the TMDL and existing loads were used to calculate percent reductions (Table C-9). Load reductions from the geometric mean TMDLs are not shown due to the lack of data to sufficiently calculate the observed geometric mean in most of the reaches.

Table C-8. *E. coli* TMDLs and Allocations.

TMDL Parameter	TMDL Component Value*
Nogales –Border to Potrero Creek	
Single Sample Maximum	
Average Flow of Representative Wet Year (cfs)	1.15
Numeric Target for TMDL (CFU/100 mL)	575
SSM TMDL (billion/day)	16.2
WLA for Nogales MS4 (billion/day)	1.0
Reserve WLA (Future Growth) (billion/day)	0.8
LA (billion/day)	14.4
Geometric Mean	
Average 2001-2010 Flow (cfs)	0.67
Numeric Target for TMDL (CFU/100 mL)	126
Geometric Mean TMDL (billion/day)	2.1
WLA for Nogales MS4 (billion/day)	0.1
Reserve WLA (Future Growth) (billion/day)	0.1
LA (billion/day)	1.8
Potrero – I-19 to SCR	
Single Sample Maximum	
Average Flow of Representative Wet Year (cfs)	4.06
Numeric Target for TMDL (CFU/100 mL)	235

TMDL Parameter	TMDL Component Value*
SSM TMDL (billion/day)	23.4
WLA for Nogales MS4 (billion/day)	1.0
Reserve WLA (Future Growth) (billion/day)	1.2
LA (billion/day)	21.2
Geometric Mean	
Average 2001-2010 Flow (cfs)	2.05
Numeric Target for TMDL (CFU/100 mL)	126
Geometric Mean TMDL (billion/day)	6.3
WLA for Nogales MS4 (billion/day)	0.1
Reserve WLA (Future Growth) (billion/day)	0.3
LA (billion/day)	5.9
SCR – Outfall to Josephine Canyon	
Single Sample Maximum	
Average Flow of Representative Wet Year (cfs)	36.87
Numeric Target for TMDL (CFU/100 mL)	575
SSM TMDL (billion/day)	518.8
WLA for Nogales MS4 (billion/day)	1.0
WLA for Nogales WWTP (billion/day)	374.4
Reserve WLA (Future Growth) (billion/day)	25.9
LA (billion/day)	117.5
Geometric Mean	
Average 2001-2010 Flow (cfs)	26.16
Numeric Target for TMDL (CFU/100 mL)	126
Geometric Mean TMDL (billion/day)	80.7
WLA for Nogales MS4 (billion/day)	0.1
WLA for Nogales WWTP (billion/day)	71.5
Reserve WLA (Future Growth) (billion/day)	4.0
LA (billion/day)	5.0
SCR – Josephine Canyon to Tubac Bridge	
Single Sample Maximum	
Average Flow of Representative Wet Year (cfs)	41.93
Numeric Target for TMDL (CFU/100 mL)	575
SSM TMDL (billion/day)	589.9
WLA for Nogales MS4 (billion/day)	1.0
WLA for Nogales WWTP (billion/day)	374.4
Reserve WLA (Future Growth) (billion/day)	29.5
LA (billion/day)	185.0

TMDL Parameter	TMDL Component Value*
Geometric Mean	
Average 2001-2010 Flow (cfs)	25.45
Numeric Target for TMDL (CFU/100 mL)	126
Geometric Mean TMDL (billion/day)	78.5
WLA for Nogales MS4 (billion/day)	0.1
WLA for Nogales WWTP (billion/day)	69.5
Reserve WLA (Future Growth) (billion/day)	3.9
LA (billion/day)	4.9
SCR – Tubac Bridge to Sopori Wash	
Single Sample Maximum	
Average Flow of Representative Wet Year (cfs)	42.91
Numeric Target for TMDL (CFU/100 mL)	575
SSM TMDL (billion/day)	603.7
WLA for Nogales MS4 (billion/day)	1.0
WLA for Nogales WWTP (billion/day)	374.4
Reserve WLA (Future Growth) (billion/day)	30.2
LA (billion/day)	198.2
Geometric Mean	
Average 2001-2010 Flow (cfs)	24.27
Numeric Target for TMDL (CFU/100 mL)	126
Geometric Mean TMDL (billion/day)	74.8
WLA for Nogales MS4 (billion/day)	0.1
WLA for Nogales WWTP (billion/day)	65.9
Reserve WLA (Future Growth) (billion/day)	3.7
LA (billion/day)	5.0

* Loads rounded to the nearest 0.1 billion (unless this would result in an allocation of zero); thus, totals may be different than the sum of their parts.

Table C-9. *E. coli* Load Reductions.

Loading Calculation	Loads and Required Reductions[2]
Nogales – Border to Potrero Creek	
TMDL (billion/day)[1]	16.2
Existing load of 2001-2010 data (billion/day)	80.8
Percent reduction from 2001-2010 loads (%)	80%
Existing load of post-upgrade data through 2010 (billion/day)	99.5
Required reduction from post-upgrade loads (%)	84%
Potrero – I-19 to SCR	
TMDL (billion/day)[1]	23.4

Loading Calculation	Loads and Required Reductions[2]
Existing load of 2001-2010 data (billion/day)	2,400
Percent reduction from 2001-2010 loads (%)	99%
Existing load of post-upgrade data through 2010 (billion/day)	2,400
Required reduction from post-upgrade loads (%)	99%
SCR – Outfall to Josephine Canyon	
TMDL (billion/day) [1]	518.8
Existing load of 2001-2010 data (billion/day)	2,209.5
Percent reduction from 2001-2010 loads (%)	77%
Existing load of post-upgrade data through 2010 (billion/day)	2,209.5
Required reduction from post-upgrade loads (%)	77%
SCR – Josephine Canyon to Tubac Bridge	
TMDL (billion/day) [1]	589.9
Existing load of 2001-2010 data (billion/day)	5,784
Percent reduction from 2001-2010 loads (%)	90%
Existing load of post-upgrade data through 2010 (billion/day)	44,214
Required reduction from post-upgrade loads (%)	99%
SCR – Tubac Bridge to Sopori Wash	
TMDL (billion/day) [1]	603.7
Existing load of 2001-2010 data (billion/day)	4,957
Percent reduction from 2001-2010 loads (%)	88%
Existing load of post-upgrade data through 2010 (billion/day)	26,502
Required reduction from post-upgrade loads (%)	98%

"—" = Not sampled; N/A = not applicable.
[1] TMDL is based on single sample maximum numeric targets.
[2] Existing loads and reductions are calculated using the 90th percentile of observed 2001-2010 data.

Allocations

There are several sources of current sources of bacteria loading to the project area. These sources have been given allocations. WLAs have been calculated for point sources while LAs have been calculated for nonpoint sources.

Load-Based Wasteload Allocations

Federal regulations (40 CFR 130.7) require TMDLs to include WLAs for each regulated point source. A portion of the allowable load was assigned based on discharge limits or developed area for the permits regularly contributing bacteria loads to the impaired reaches (the small MS4 general permit for Nogales and the Nogales WWTP near Rio Rico) as well as for future permittees.

Wasteload Allocations: Nogales WWTP

One NPDES permitted WWTP, the Nogales WWTP, discharges to the USCR project area at the beginning of the USCR – Outfall to Josephine Canyon segment. The treatment plant effluent influences the three impaired segments of the USCR main stem. Because this facility is identified as a potential source of *E. coli* within the impaired reach, the facility is assigned a WLA in this TMDL. For the single sample maximum TMDL, load-based WLAs were calculated based on the design flow capacity (17.2 mgd or 26.6 cfs) and the existing daily maximum permit limit of 575 CFU/100mL (equaling 374.4 billion/day). For the average condition TMDL, the average effluent rate (15 mgd) and the existing permit limit for average conditions (126 CFU/100mL) were multiplied with the conversion factor to determine the WLA for the SCR – Outfall to Josephine Canyon (equaling 71.5 billion/day). Since flow infiltrates into groundwater and evaporation and evapotranspiration contribute to stream losses moving downstream, 2.8 and 7.8 percent reductions were applied to the WLA for SCR – Josephine Canyon to Tubac Bridge and SCR – Tubac Bridge to Sopori Wash segments, respectively. These reductions in the WLA account for the losses in flow moving downstream from the outfall and represent the differences in the average SWAT model flow between the outfall reach and the two downstream segments. Table C-10 presents the WLAs for each reach.

Table C-10. Load-based *E. coli* WLAs for the Nogales WWTP.

Segment	Single Sample Maximum *E. coli* WLA (billion/day)	Geometric Mean *E. coli* WLA (billion/day)
Nogales – Border to Potrero Creek	N/A	N/A
Potrero – I-19 to SCR	N/A	N/A
SCR – Outfall to Josephine Canyon	374.4	71.5
SCR – Josephine Canyon to Tubac Bridge	374.4	69.5
SCR – Tubac Bridge to Sopori Wash	374.4	65.9

N/A = not applicable; the outfall does not discharge to these reaches.

Wasteload Allocations: Nogales MS4

Nogales, Arizona is subject to small MS4 general permit requirements (Permit No. AZG2002-002). There are 3.67 square miles of developed area in the city of Nogales, which is 6 percent of the overall Nogales subbasin area. This developed municipal area was assigned load-based WLA based on its area-weighted portion of the allowable load in the Nogales – Border to Potrero Creek drainage. Specifically, the single sample maximum loading capacity for Nogales – Border to Potrero Creek was 16.2 billion *E. coli* per day. The Nogales MS4 WLA is 6 percent of this load, or 1.0 billion *E. coli* per day (Table C-8). Similarly, the geometric mean loading capacity was 2.1 billion *E. coli* per day (Table C-8), resulting in a geometric mean WLA of 0.1 billion *E. coli* per day for the Nogales MS4. Compliance with this WLA shall be assessed within the MS4 area itself and represents the total loading for the MS4, not a load for each outfall.

Table C-11. Load-based *E. coli* WLAs for the Nogales MS4.

Segment	Single Sample Maximum *E. coli* WLA (billion/day)	Geometric Mean *E. coli* WLA (billion/day)
Nogales – Border to Potrero Creek	1.0	0.1
Potrero – I-19 to SCR	1.0	0.1
SCR – Outfall to Josephine Canyon	1.0	0.1
SCR – Josephine Canyon to Tubac Bridge	1.0	0.1
SCR – Tubac Bridge to Sopori Wash	1.0	0.1

Wasteload Allocation: General Permits

Concentration-based WLAs were applied to all existing and future general permittees within the project area. Most general permit facilities are not reasonably expected to generate *E. coli* by their operations; therefore, they are not assigned load-based WLAs. All individual and general AZPDES permittees will be considered to be operating consistent with this TMDL if they adhere to the terms of their discharge permits as expressed for *E. coli* concentrations.

Wasteload Allocations: Future Growth

Potential future sources of bacteria to the project area include, but are not limited to, CAFOs. If CAFOs or other facilities are permitted in the project area in the future, they will be subject to a future growth WLA that was developed to account for any future permitted sources. This load-based future growth WLA was calculated as 5 percent of the single sample maximum and geometric mean loading capacities for each segment. For example, in Nogales – Border to Potrero Creek the single sample maximum loading capacity was 16.2 billion *E. coli* per day (Table C-8). The future growth WLA was calculated as 5 percent of this load, or 0.8 billion *E. coli* per day. This WLA, summarized in Table C-12, establishes a reserve capacity from which future permittees can draw in each impaired segment.

Table C-12. Load-based *E. coli* WLAs for Future Growth.

Segment	Single Sample Maximum *E. coli* WLA (billion/day)	Geometric Mean *E. coli* WLA (billion/day)
Nogales – Border to Potrero Creek	0.8	0.1
Potrero – I-19 to SCR	1.2	0.3
SCR – Outfall to Josephine Canyon	25.9	4.0
SCR – Josephine Canyon to Tubac Bridge	29.5	3.9
SCR – Tubac Bridge to Sopori Wash	30.2	3.7

Load-Based Load Allocations

According to federal regulations (40 CFR 130.2(g)), load allocations are best estimates of the nonpoint source or background loading. Within this TMDL, load allocations were assigned to the loads remaining after the cumulative WLAs were subtracted from the loading capacity. For example, in Table C-8, the WLAs for a given reach can be summed and then subtracted from the loading capacity, resulting in the load allocation. The LA values by segment are shown in Table C-13 for both the single sample maximum and geometric mean TMDLs.

Table C-13. Load-based *E. coli* LAs by segment.

Segment	Single Sample Maximum *E. coli* WLA (billion/day)	Geometric Mean *E. coli* WLA (billion/day)
Nogales – Border to Potrero Creek	14.4	1.8
Potrero – I-19 to SCR	21.2	5.9
SCR – Outfall to Josephine Canyon	117.5	5.0
SCR – Josephine Canyon to Tubac Bridge	185.0	4.9
SCR –Tubac Bridge to Sopori Wash	198.2	5.0

Nonpoint source loads in the project area include loading from cattle, wildlife, septic systems, recreational activities, and unpermitted inputs to Nogales Wash from Mexico, such as temporary communities near the border. Information obtained from the SWAT modeling (Appendix A) was used to estimate relative contributions from these sources to guide implementation (Figure C-68 through Figure C-72). Specifically, the proportion of cattle, wildlife, and human sources estimated for each segment from the SWAT model was applied to the single sample maximum LAs in Table C-13 and summarized in the pie charts below. These results are subject to the caveats and assumptions described in Appendix A. It is important to note that human nonpoint source loading from temporary communities near the border are likely underestimated by the SWAT model (Appendix A) as this source was not explicitly entered in the model because model inputs are associated with specific land uses and there was no separate category for urban inputs from Mexico, which is expected to have different characteristics than urban land in Arizona. Loading from Mexico is also demonstrated by the impairment analysis and water quality duration curves presented in Sections 5.2.2 and 5.3.2.2.1 of the CWP, respectively.

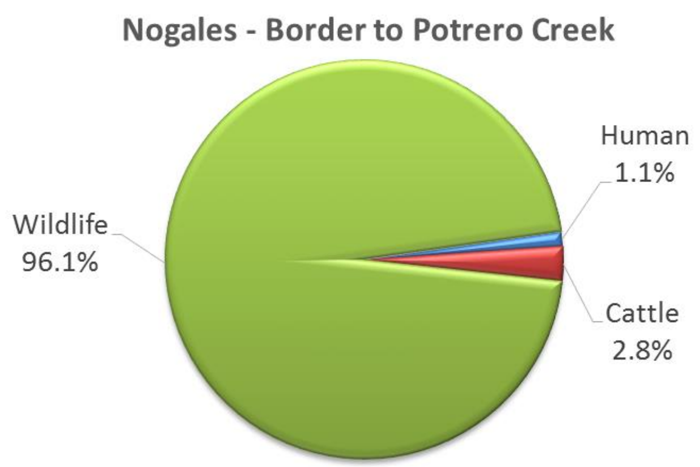

Figure C-68. Relative Nonpoint Source Loads to Nogales– Border to Potrero Creek.

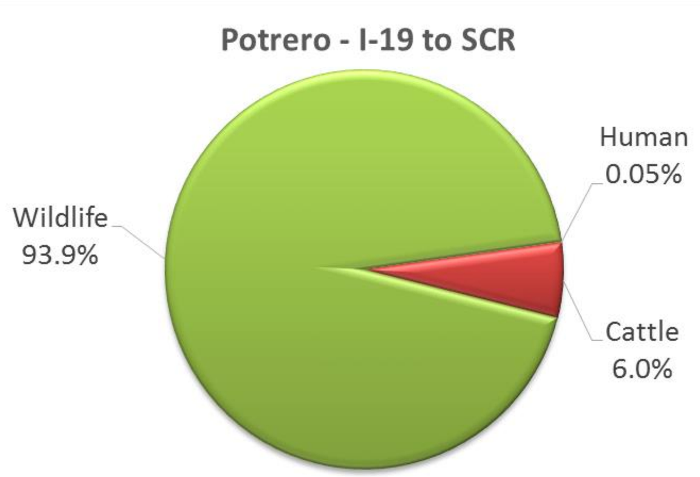

Figure C-69. Relative Nonpoint Source Loads to Potrero – I-19 to SCR.

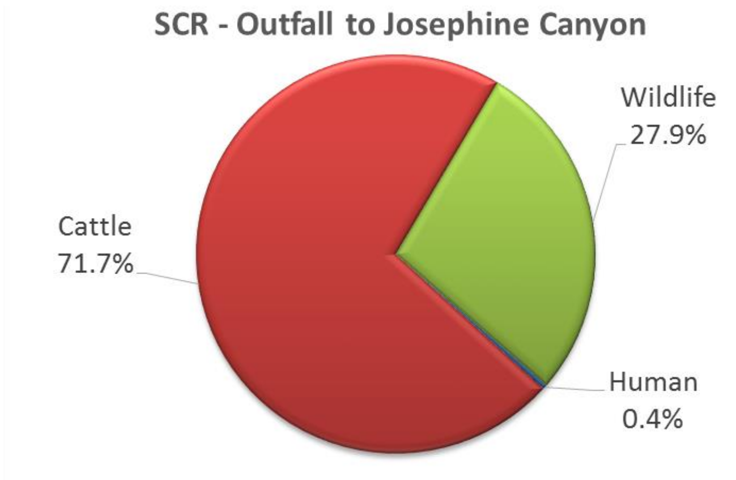

Figure C-70. Relative Nonpoint Source Loads to SCR – Outfall to Josephine Canyon.

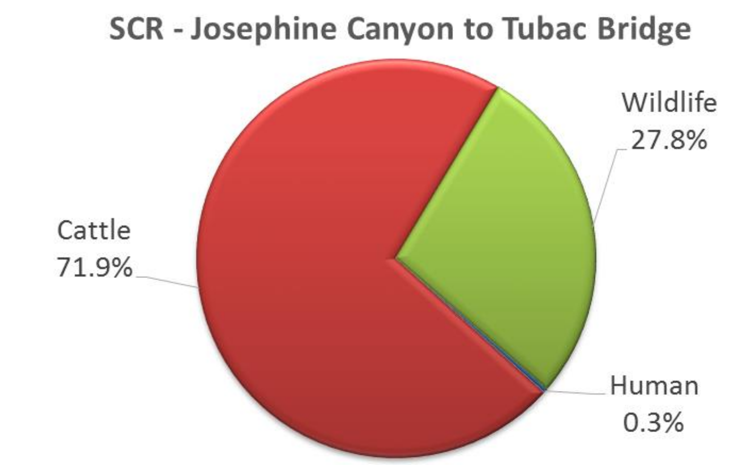

Figure C-71. Relative Nonpoint Source Loads to SCR – Josephine Canyon to Tubac Bridge.

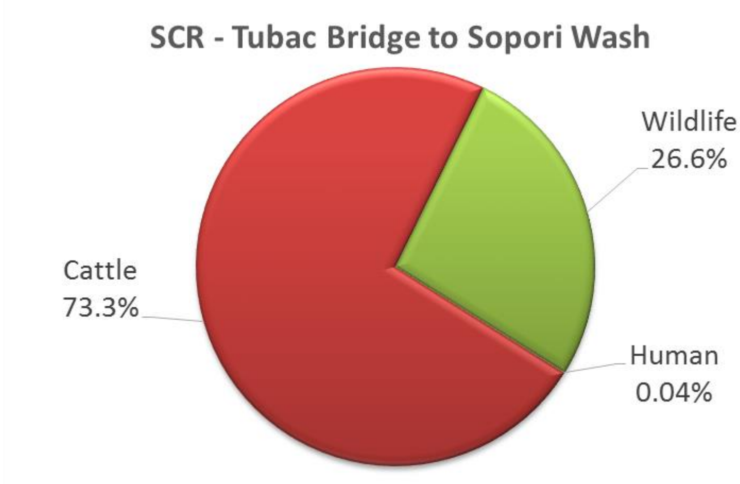

Figure C-72. Relative Nonpoint Source Loads to SCR – Tubac Bridge to Sopori Wash.

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Appendix D

Satellite Imagery Survey

October, 2018

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For the satellite imagery survey, ADEQ utilized Google My Maps to visually survey the watershed and identify areas that may potentially contribute *E. coli* or sediment to the Santa Cruz River. Google My Maps was utilized to allow for a collaborate review of the multiple subbasins throughout the watershed. The purpose of the survey is to identify potential areas of concern for contributions to nonpoint source pollution. These included stock tanks, corrals, and possible areas of erosion.

Reviews of subbasins were completed by ADEQ staff. Subbasins were grouped into five areas and assigned to individual reviewers to identify areas of concern.

Figure D-1.Map showing the grouping of subbasins for review.

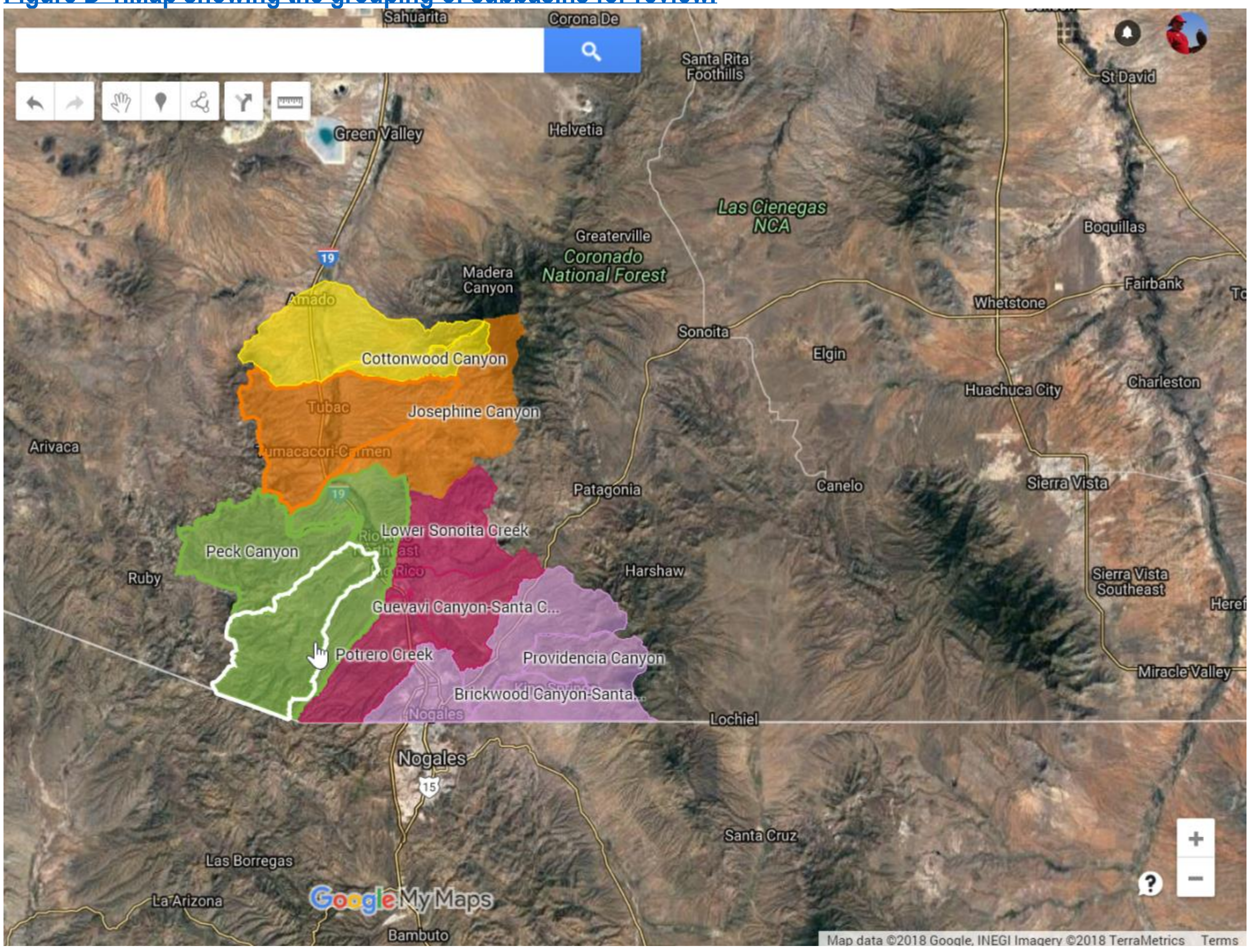
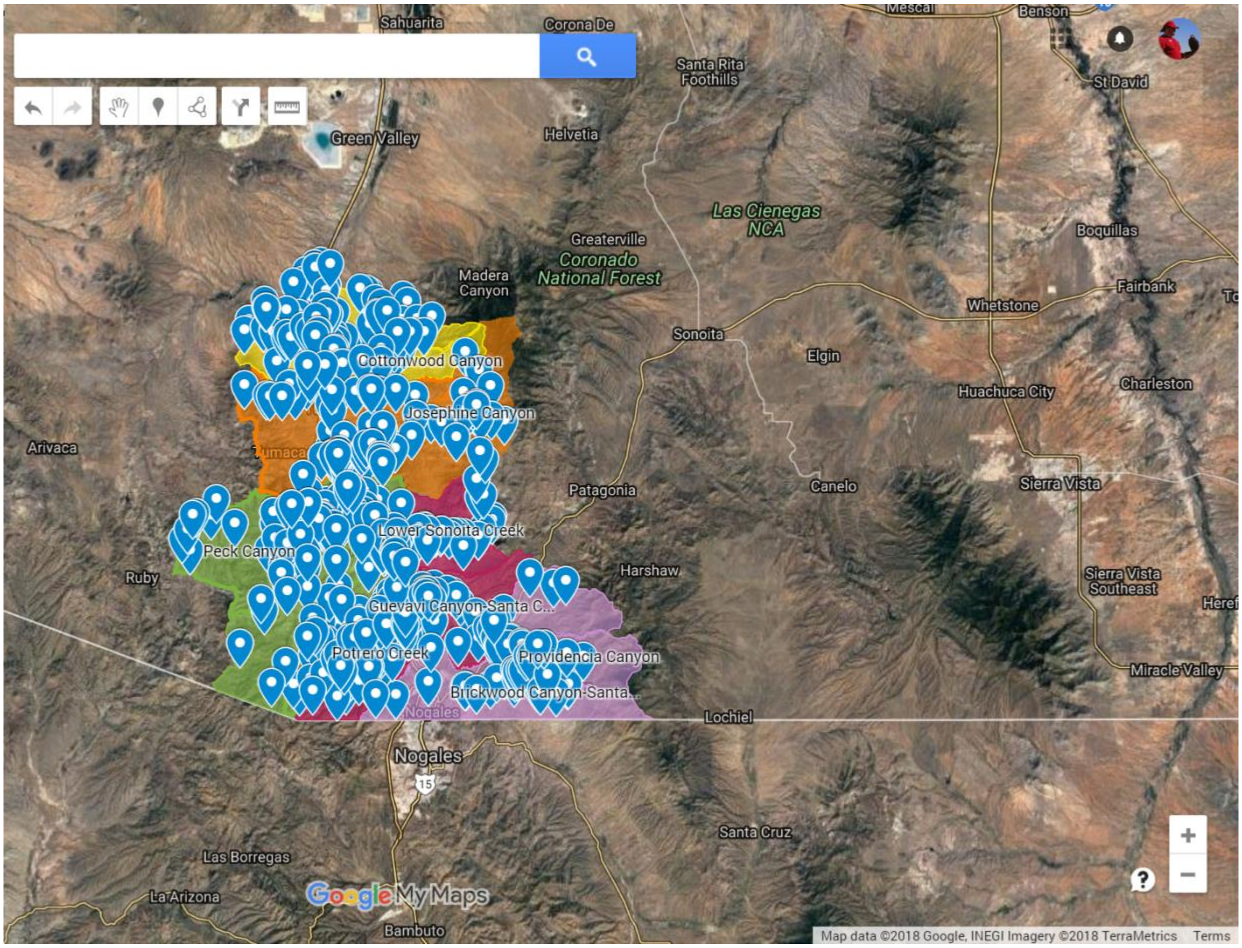
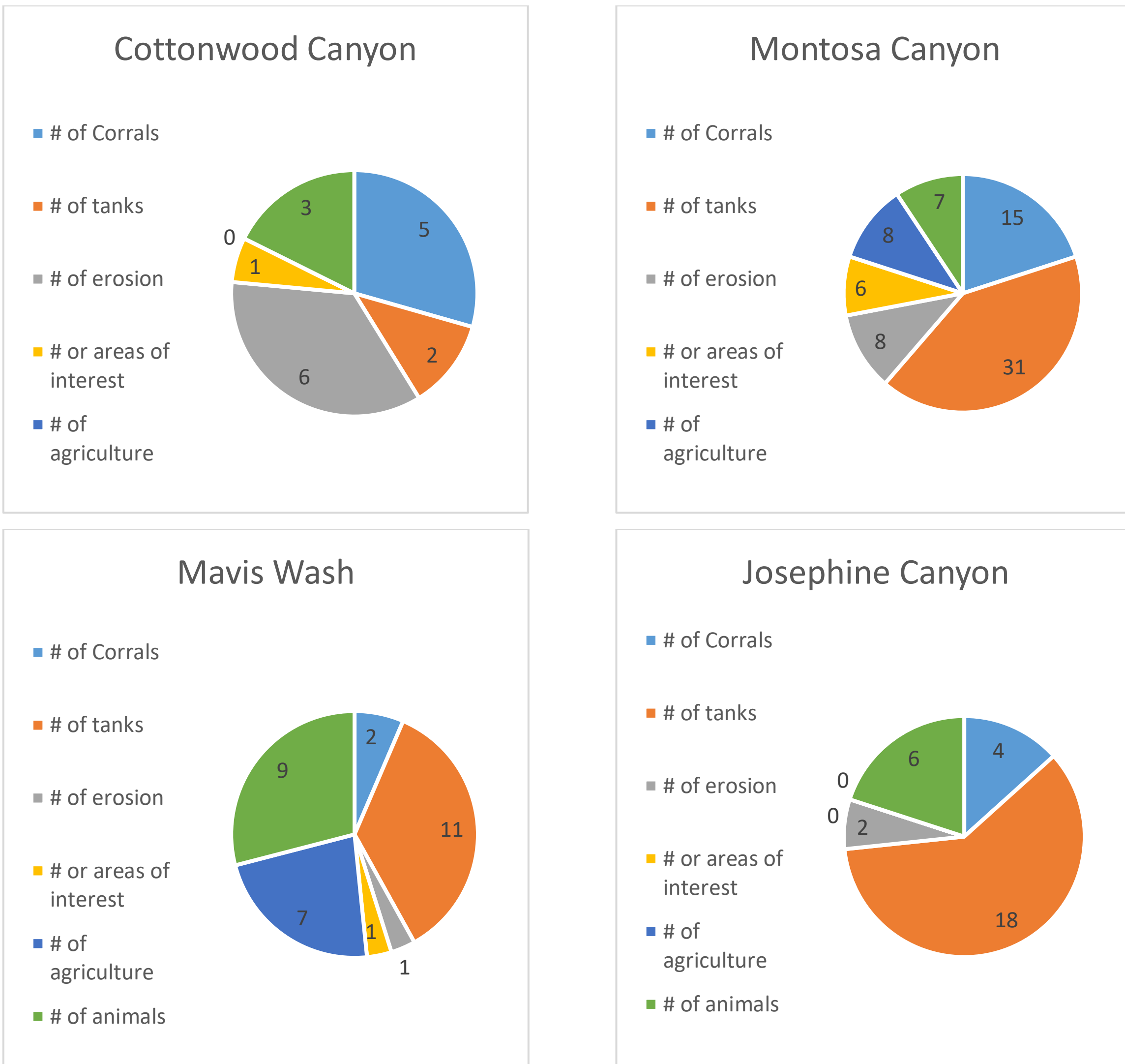


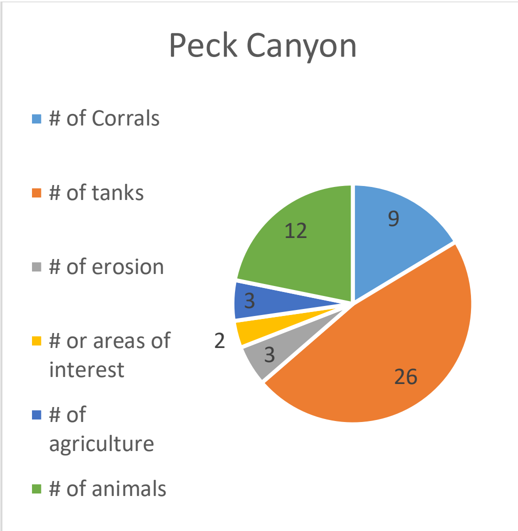
Figure D-2. Map showing the markers identifying areas of concern throughout the watershed.

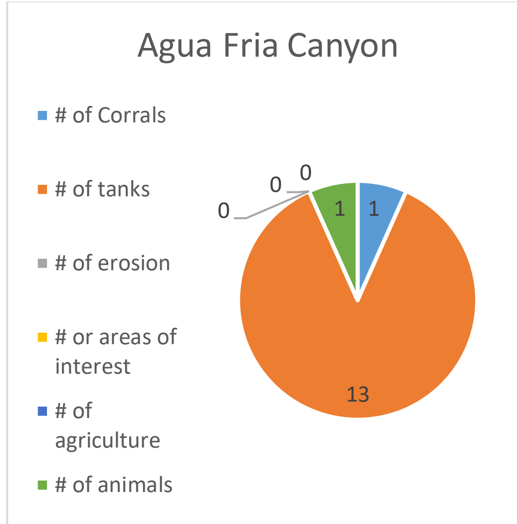


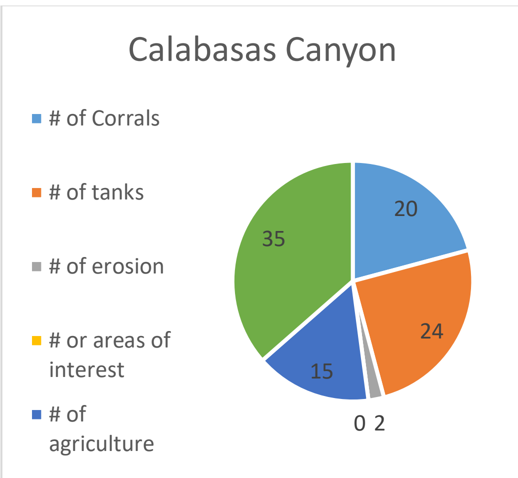
Reviewers used the Add Marker tool to identify and label any areas of concern. This information was then extracted to a spreadsheet format to analyze the data. Data was analyzed by subbasin and summarized in the figure below.

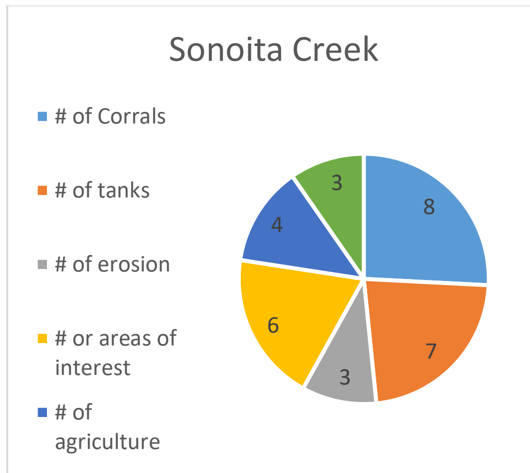
Figure D-3. Subwatershed data showing a breakdown of types and numbers of potential sources

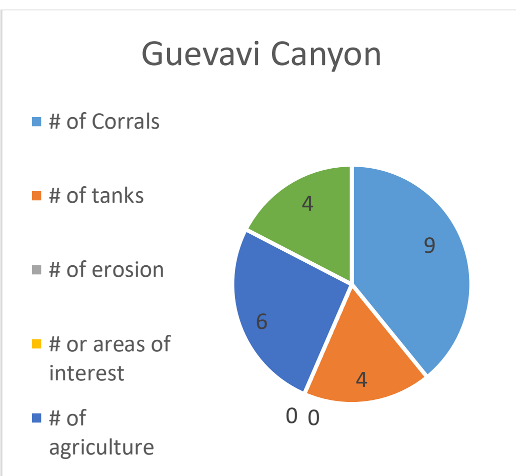


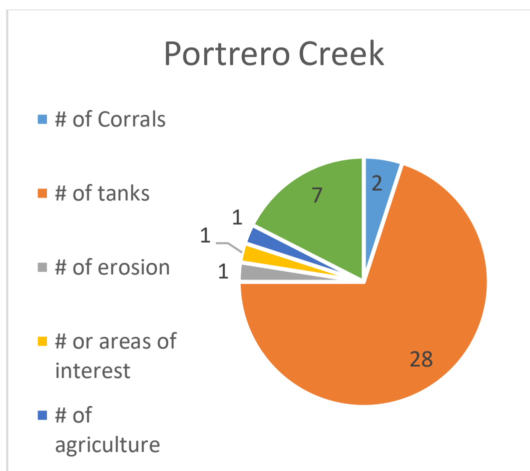

Peck Canyon
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
# of animals
9
26
3
2
3
12

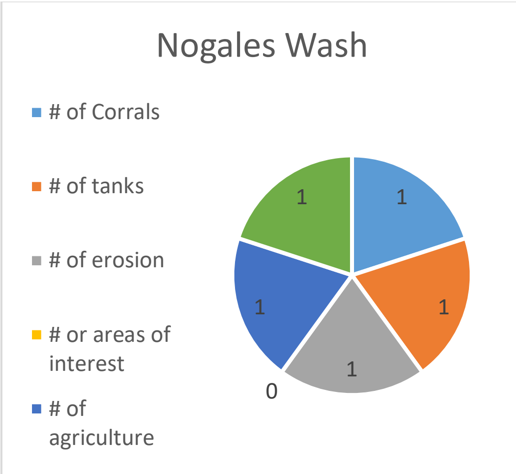

Agua Fria Canyon
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
# of animals
1
13
0
0
0
1

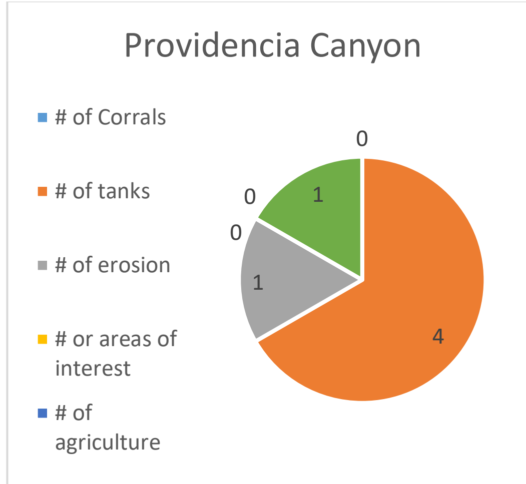

Calabasas Canyon
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
20
24
2
0
15
35

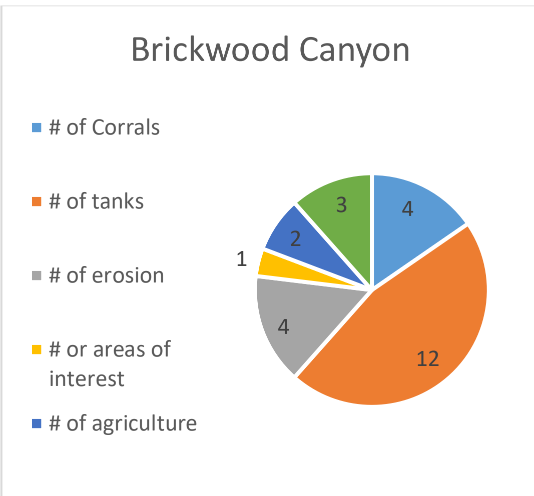

Sonoita Creek
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
8
7
3
6
4
3

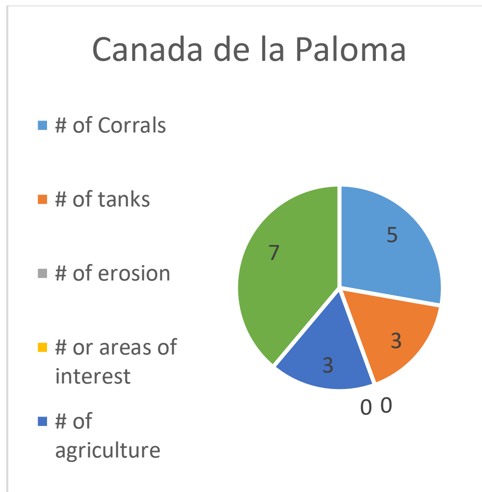

Guevavi Canyon
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
9
4
0
0
6
4


Portrero Creek
# of Corrals
# of tanks
# of erosion
or areas of interest
of agriculture
2
28
1
1
1
7









The data from the satellite survey was also used to determine the percentage of each possible source within the respective subwatersheds based on the total number of sources identified throughout the entire upper Santa Cruz River watetrshed. Table D-1 shows the breakdown of data for each subwatershed.

Table D-1. Percentage of possible pollutant sources for each subwatershed

Subbasin	% of Concerns	# of Corrals	# of tanks	# of erosion	# or areas of interest	# of agriculture
Montosa Canyon	18.43%	4.07%	8.40%	2.17%	1.63%	2.17%
Calabasas Canyon	16.53%	5.42%	6.50%	0.54%	0.00%	4.07%
Peck Canyon	11.65%	2.44%	7.05%	0.81%	0.54%	0.81%
Portrero Creek	8.94%	0.54%	7.59%	0.27%	0.27%	0.27%
Sonoita Creek	7.59%	2.17%	1.90%	0.81%	1.63%	1.08%
Josephine Canyon	6.50%	1.08%	4.88%	0.54%	0.00%	0.00%
Brickwood Canyon	6.23%	1.08%	3.25%	1.08%	0.27%	0.54%
Mavis Wash	5.96%	0.54%	2.98%	0.27%	0.27%	1.90%

Subbasin	% of Concerns	# of Corrals	# of tanks	# of erosion	# or areas of interest	# of agriculture
Guevavi Canyon	5.15%	2.44%	1.08%	0.00%	0.00%	1.63%
Cottonwood Canyon	3.79%	1.36%	0.54%	1.63%	0.27%	0.00%
Agua Fria Canyon	3.79%	0.27%	3.52%	0.00%	0.00%	0.00%
Canada de la Paloma	2.98%	1.36%	0.81%	0.00%	0.00%	0.81%
Providencia Canyon	1.36%	0.00%	1.08%	0.27%	0.00%	0.00%
Nogales Wash	1.08%	0.27%	0.27%	0.27%	0.00%	0.27%